Cybersickness in Virtual Reality Head-Mounted Displays: Examining the Influence of Sex Differences, Vehicle Control and Postural Precursors

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Abstract

The auspicious future of virtual reality could be thwarted by cybersickness. Cybersickness can be thought of as a subset of motion sickness and like motion sickness is more common among women than among men. Additionally, motion sickness is more common among passengers than among drivers. In this dissertation research, it was asked whether these two effects might interact. In a yoked-control design using a head-mounted display, one member of each pair drove a virtual automobile, while the other member watched a recording of the driver's performance. In Chapter 2, it is explored whether such an interaction existed and the overall rates of cybersickness amongst these two groups. Previous research has shown that the subjective experience of cybersickness often is preceded by distinctive patterns of movement. In Chapter 3, it is examined whether such postural precursors of cybersickness might exist before participants were exposed to a virtual driving game presented. In this chapter, participants standing body sway was gathered while participants performed simple visual tasks (staring at a blank page vs. counting target letters in a block of text). In Chapter 4, movement of the head and torso was recorded while participants were exposed to a driving video while seated. These three chapters further inform the current understanding of cybersickness, and whether certain factors of the virtual environment may increase the likelihood of individuals becoming cybersick. Furthermore, chapters 3 and 4 further explore whether movement data can be used as an objective predictor in cybersickness research. If movement data further proves to be an objective predictor then this approach can be one

of many approaches to assuage cybersickness for highly susceptible individuals.

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List of Abbreviations

Abbreviation	Explanation
M	Meters
CM	centimeters
Min	Minutes
Kg	Kilograms
Hz	Hertz
COP	Center of Pressure
AP	Anterior-posterior
ML	Mediolateral
HMD	Head-mounted display
SSQ	Simulator Sickness Questionnaire
VR	Virtual Reality
IRB	Institutional Review Board
SD	Standard deviation
SE	Standard error of the mean
MF DFA	Multifractal detrended fluctuation analysis
DFA	Detrended fluctuation analysis
ANOVA	Analysis of variance
CI	Confidence interval

Chapter 1: Introduction

Motivation

Virtual reality (VR) systems are expanding beyond entertainment. Increasingly, VR has shown its practical benefits in various domains including education and healthcare, to name a couple (Ahlberg et al., 2007; Hoffman et al., 2011). VR can be described as an interactive computer-simulated environment (Rebenitsch & Owen, 2016). These virtual environments can be presented through the use of head-mounted displays (HMD). HMDs can be described as a headset equipped with visual display screens, as well as motion sensors. Using the HMD, the user can interact with their virtual environments in a naturalistic way. For instance, the user can walk-around and look-around their virtual environments, akin to how they would in everyday life.

One issue that has impacted a portion of users is motion sickness, often referred to as cybersickness. Cybersickness is a term commonly used to refer to the subset of motion sickness that occurs among users of VR systems (McCauley & Sharkey, 1992). Cybersickness can include a variety of symptoms, including nausea, eyestrain, and disorientation, to name a few. Symptoms of cybersickness can last a few minutes to even a day after exposure. Stanney et al., (2002) gathered data from participants a day after they had used an HMD and found that 17% of their participants reported higher symptoms compared to their baseline scores.

Symptoms of cybersickness can be so profound that it can result in discontinuation of the experience. In an extensive review (2015) Lawson found that 61%

to 80% of participants in various studies experienced symptoms related to cybersickness. These symptoms can result in premature termination. For instance, Lawson found that 17% of research participants discontinued before the completion of the study. Discontinuation is relatively inconsequential in entertainment applications but can have serious consequences in industrial and medical applications. Furthermore, even with technological advancements, it does not appear that the issue of cybersickness is declining (Rebenitsch & Owen, 2016).

Theories on Motion Sickness

To understand why individuals become cybersick, it is imperative to understand current theories on motion sickness. The two most prominent ones are the Sensory Conflict Theory and the Postural Instability Theory. Sensory Conflict claims that motion sickness is the result of discrepancies between sensory inputs with expectations based on past experiences (Oman, 1982). For instance, if a user is sitting down, but they are exposed to visual cues consistent with self-motion, then this would result in a mismatch, leading to motion sickness. A criticism of Sensory Conflict is that it is a post-hoc explanation for motion sickness and cannot be used to dynamically predict those that will become sick (Oman, 1982).

While Sensory Conflict has often been used as a post-hoc explanation, Postural Instability Theory has demonstrated its ability at predicting those that will become motion sickness with a high degree of accuracy (Smart et al., 2002). Postural Instability Theory suggests that a person who experiences motion sickness should display distinctive patterns of postural activity, which differ from someone that does not become sick (Riccio & Stoffregen, 1991). Furthermore, Postural Instability Theory posits that postural instability is the cause of motion sickness and that postural instability precedes symptoms of motion sickness. Therefore, if a participant can remove themselves from situations that would cause unstable posture, then they should see a reduction in motion sickness severity and symptoms. Similarly, interventions that act to stabilize posture should yield reductions in cybersickness.

Through the use of kinematic measurement devices, research studies have provided evidence in support of Postural Instability Theory. Kinematic data have been collected in myriad studies since the proposal of Postural Instability Theory showing its validity in multiple applications (e.g., flight simulators (Stoffregen, Hettinger, Haas, Roe & Smart, 2000), cruise ships (Stoffregen, Chen, Varlet, Alcantara & Bardy, 2013), and video games (Stoffregen, Faugloire, Yoshida, Flanagan & Merhi, 2008). Additionally, kinematic data has been collected from participants while they sat or stood. In the following subsections, a few of these research studies will be presented to provide support for Postural Instability Theory's claim.

Movement Data Collected While Sitting

Evaluation of this theory from a seated position has occurred during the use of commercial video games (Dong, Yoshida, & Stoffregen, 2011; Stoffregen, Chen & Koslucher, 2014). In these studies, motion sickness severity was assessed using the Simulator Sickness Questionnaire (SSQ) and placement into the sick/well group was determined based on a forced-choice, yes/no question, *Are you motion sick?* (Kennedy, Lane, Berbaum & Lilienthal, 1993). Dong et al. (2011) found differences in movements of the head and torso in the anteroposterior axis (AP), for sick and well groups during the use of console game displayed via a TV monitor. These findings were later replicated by Stoffregen, Chen, and Koslucher (2014) who had participants play a commercial game via a computer tablet. In addition to showing differences between sick and well groups in the AP axis for the head and torso, differences were also observed in the mediolateral (ML) of the head. The results of these two studies showed differences in magnitude and variability of body sway and were not restricted to one presentation format. In addition to presenting differences in posture, both studies showed the sick group reported greater severity of motion sickness assessed by SSQ responses. This finding is also consistent with Postural Instability Theory which suggests that the longer a participant is in a period of instability, the greater severity of symptoms.

Movement Data Collected While Standing

Similar to the presence of motion sickness from a seated position, kinematic data has been collected from a standing position to provide additional support for Postural Instability Theory. Such data collection has occurred during exposure to a moving room that oscillated in a potentially nauseogenic way (Stoffregen & Smart, 1998). In their study, Stoffregen and Smart conducted two experiments with the second experiment conducted for replication purposes. In both experiments during the ten-minute trials, participants that were placed in the sick group had significantly larger head movement in the ML axis compared to the well group. Additionally, participants in the sick group saw a larger increase in motion sickness severity assessed by SSQ scores.

Movement data during stance has also been collected during exposure to a commercial video game presented via an HMD (Stoffregen et al., 2008). In their study, Stoffregen and colleagues found participants in the well group had a significantly higher velocity of head movements and significantly higher variability in torso movements. While these results differ from the previous studies discussed, Postural Instability Theory suggests movement will differ between sick and well groups, which is consistent with the theory. Nonetheless, consistent with previous studies, participants in the sick group had higher severity of motion sickness compared to the well group. The results of these studies show that differences in body sway occur for sick and well group during stance and are not limited to one type of potential nauseogenic exposure.

In this dissertation research, the Postural Instability Theory was chosen as the theoretical framework based on its capacity to predict those who will become cybersick in real-time rather than providing a post-hoc explanation. To further understand the relationship between postural instability and cybersickness, kinematic data while participants were seated and standing was collected. Kinematic data was collected prior to participants donning the HMD (standing position) and during exposure to a virtual environment (seated position). The decision to collect kinematic data prior to exposure was based on Munafo et al. (2017) who demonstrated that standing body sway differed between participants that became cybersick and those that did not.

Sex Differences

A strategy for the mitigation is to identify individuals who are more sensitive to cybersickness, such that interventions can be implemented before the onset of subjective symptoms. Susceptibility to cybersickness naturally varies between individuals. One individual factor that is known to influence susceptibility is sex. Motion sickness has been shown to be greater for females than males in multiple settings. For instance, Lawther and Griffin (1988) interviewed 20,000 passengers on sea-going ferries and found that females became sick at a rate of 5:3. In a laboratory setting, 38% of females became motion sick compared to only 9% of males when exposed to a moving room (Koslucher et al., 2015). These sex differences have also been shown in cybersickness research. In Munafo et al. (2017) it was shown in one of two of their experiments that females became cybersick at a ratio of 2:1.

Sex differences such as these can have discriminatory repercussions if VR applications are used in everyday settings. For instance, female physicians might have reduced ability to practice telemedicine or mental health therapists may be hesitant to recommend VR to help treat a disorder with a female patient. To further shed light on these sex differences with VR devices, this research project further investigated the differences in cybersickness amongst males and females.

Situations that Heighten Motion Sickness

A potential solution to reduce cybersickness is through the virtual environment. To understand how to design a virtual environment to reduce cybersickness, it is imperative to fully understand what situations cause motion sickness to occur more frequently. One such situation is being in control of your setting. Anecdotal reports suggest that drivers are less likely to become motion sick compared to passengers (Geeze & Pierson, 1986). This difference between drivers and passengers has often been referred to as the driver-passenger effect. Rolnick and Lubow (1991) investigated the driver-passenger effect using a whole-body motion device that rotated around the vertical axis. This apparatus carried two participants. One participant was in control of the device, while the other participant was not. Their study found that the participant in control of the device tended to report fewer symptoms of motion sickness than the participant who was not in control.

Dong et al. (2011) explored the driver-passenger effect in a virtual setting. In their study, they utilized a yoked control assigning one participant to the “driver” group and another participant to the “passenger” group. Participants in the driver group were in control of a virtual vehicle using a gamepad. The virtual environment was displayed on a plasma flat screen display (1.65 m diagonal). Footage from the driving participants was recorded and played for participants in the passenger group. This method of recording gameplay footage from the driver and playing it for the passenger ensured the visual stimuli were the same and the only difference was the element of being in control of the virtual environment. The results of Dong et al. found that the passenger group was more likely to report the incidence of motion sickness compared to participants in the driver group. In addition to collecting the incidence of motion sickness, Dong et al. gathered kinematic data while participants were exposed to the virtual environment. In an attempt to replicate Dong et al. (2011) and Rolnick and Lubow (1991) studies, this current study explored the driver-passenger effect using HMDs.

Purpose of the Study

The purpose of this dissertation project was to further an understanding of cybersickness in VR HMDs. With the continued rise of VR devices, it is important to explore ways to negate cybersickness. By having a firm understanding of what factors heighten cybersickness, only then can such efforts be undertaken.

This project explored whether postural patterns differ between individuals that become cybersick and those that do not. Previous research has demonstrated that postural precursors differ between those who become sick and those who do not (Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016). Based on these past studies, it has been demonstrated that body sway characteristics are a sensitive objective predictor of symptoms of motion sickness. Kinematic data in this study will be collected prior to participants donning the HMD, as well as during exposure.

In addition to gathering kinematic data before and during exposure, this current project further explored the "driver-passenger" effect and whether this effect can be replicated using an HMD. Previous motion sickness research has shown that a driver is less likely than a passenger to report symptoms of motion sickness (Rolnick & Lubow 1991; Dong et al., 2012). Lastly, this project delved further into understanding the sex differences commonly seen in motion sickness studies (Lawther & Griffin, 1988; Koslucher et al., 2015).

Goals and Hypotheses

Based on the previously reviewed literature, the following research project was developed which will examine cybersickness in VR HMDs. In this experiment, the goals of this project were to 1) understand how the driver-passenger effect would differ between men and women 2) examine whether the driver-passenger effect would occur in an HMD 3) investigate postural precursors of cybersickness 4) study how postural activity during exposure differs between those that become cybersick and those that do not.

In total, 79 participants were recruited (41 females and 38 males) to address these four goals. To the best of the experimenter's knowledge, he is not aware of any studies, either observational or experimental, of possible sex differences in motion sickness relating to drivers and passengers of either physical or virtual vehicles.

The following hypotheses were made:

- H1: Females will have a higher incidence and higher severity of cybersickness than males.
- H2: Participants in the passenger group will have a higher incidence and higher severity of cybersickness.
- H3: There will be statistically significant interactions that include Sickness Groups, Sex, and Control in the postural movement patterns prior to donning the HMD.

- H4: There will be statistically significant interactions that include Sickness Groups, Sex, and Control in the postural movement patterns while wearing the HMD.

Overview of the Remainder of this Dissertation

Chapters 2-4 in this dissertation each were published separately. However, the data set that was used in each of these publications was collected concurrently and therefore there will be similarities in each of these. Nonetheless, each of these chapters present novel findings and separately seek to address the problem of cybersickness in HMDs.

In total 79 participants participated in this experiment. However, it should be noted that because of technological difficulties and exposure time requirements, data from 65 individuals were analyzed rather than 79 for Chapter 4. In Chapter 2, hypotheses 1 and 2 will be examined. Chapter 3 will address hypothesis 3. And lastly, Chapter 4 will address hypothesis 4.

In this dissertation, Chapter 2 corresponds to Curry et al., 2020a; Chapter 3 corresponds to Curry et al., 2020b; Chapter 4 corresponds to Curry et al., 2020c.

Chapter 2: Cybersickness in Virtual Reality Head-Mounted Displays: Examining the Influence of Sex Differences and Vehicle Control

Introduction

It is a commonplace observation that automobile passengers are more likely than drivers to experience motion sickness. This “driver-passenger” effect has been confirmed experimentally in physical vehicles (Rolnick & Lubow, 1991) and in virtual vehicles (Dong, Yoshida, & Stoffregen, 2011). This chapter focused on two aspects of the driver-passenger effect. First, this chapter will explore whether the driver-passenger effect would differ between men and women. Second, it was asked whether the driver-passenger effect would occur in the context of head-mounted displays (HMDs). HMDs are remarkable technical achievements, and often give rise to compelling subjective experiences of realism, or presence. Unfortunately, these systems are associated with motion sickness, which is often referred to as cybersickness.

Cybersickness is a term commonly used to refer to the subset of motion sickness that occurs among users of virtual reality systems (McCauley & Sharkey, 1992). Regardless of the term used to refer to this phenomenon, there are widespread anecdotal reports in controlled research confirming the occurrence of motion sickness in HMDs (Draper, Viirre, Furness, & Gawron, 2001; Merhi, Faugloire, Flanagan, & Stoffregen, 2007; Munafo, Diedrick, & Stoffregen, 2017; Sharples, Cobb, Moody, & Wilson, 2008).

Accordingly, HMDs seemed a good venue to investigate possible sex differences in the driver-passenger effect.

Sex differences

In most situations, women are more susceptible to motion sickness than men. Classic studies have documented this effect in seasickness and other types of vehicular travel (Golding, 2006; Lawther & Griffin, 1988; Turner & Griffin, 1999). Women also are more susceptible than men in the context of visually induced motion sickness (e.g., Koslucher, Haaland, Malsch, Webeler, & Stoffregen, 2015).

Sex differences in motion sickness may be especially problematic in HMDs. In two experiments, Munafo et al. (2017) examined motion sickness among users of a contemporary HMD system (the Oculus Rift DK-2). While playing a non-locomotor game (Experiment 1), in which rotational head movements were used to manipulate a game board, the difference in incidence between women and men was not significant. However, while playing a locomotor game (Experiment 2), in which the player used a handheld controller to walk freely within a virtual building, women (78%) were significantly more likely than men (33%) to state that they were motion sick. In this chapter, it was asked whether sex differences in visually induced motion sickness would extend to a virtual vehicle presented via an HMD.

Men and women, drivers and passengers

Rolnick and Lubow (1991) documented the driver-passenger effect in the context of inertial motion. They built a whole-body motion device that rotated around the vertical axis, carrying two participants. One participant controlled the rotation of the device, while the other did not. Participants in control of the device reported fewer symptoms of motion sickness than participants who were not in control. However, the experimental sample included only males. Several studies have examined the driver-passenger effect in the context of visually induced motion sickness, using virtual vehicles in video games. These studies have included women and men but have not analyzed the data for possible sex differences (e.g., Chang, Chen, Kung, & Stoffregen, 2017; Dong et al., 2011; Stoffregen, Chang, Chen, & Zeng, 2017; cf., Chen, Dong, Chen, & Stoffregen, 2012; Sharples et al., 2008; Stoffregen, Chen, & Koslucher, 2014). Accordingly, the existing literature provides no information about possible sex differences in the driver-passenger effect.

Given the generality of sex differences in motion sickness, it seems appropriate to ask whether differences between women and men may co-vary with the control of vehicles. Given the ubiquity of automobile travel, and the fact most adults have wide experience traveling as drivers and as passengers, it may seem remarkable that this question has not been addressed. Nevertheless, the experimenter is not aware of any studies, either observational or experimental, of possible sex differences in motion sickness relating to drivers and passengers of either physical or virtual vehicles. The present chapter was part of a larger project in which also investigated the relationships between motion sickness and the kinematics of body sway: these data are presented in Chapters 3 and 4.

Method

Participants

A total of 79 individuals participated (41 women and 38 men), in exchange for course credit. Participants ranged in age from 18 to 49 years (mean = 21.84 years, SD = 4.19 years), in height from 1.51 to 1.94 m (mean = 1.72 m, SD = 0.10 m), and in weight from 47.63 to 104.33 kg (mean = 71.58 kg, SD = 12.47 kg). The research protocol was approved in advance by the IRB of the University of Minnesota IRB (STUDY00001875).

Apparatus

I used the Oculus Rift CV1. The device comprised a lightweight (0.360 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with 1080 × 1020 resolution, yielding a 100° horizontal field of view. A lens located in front of each display rendered display content at optical infinity.

Participants used the Oculus Rift while seated on a stool. The stool had no back and was built in such a way that the participant could rotate freely; that is, they could rotate around the vertical axis of the stool. So long as they remained seated on the stool, they were permitted to move in any way that they wished. Drivers controlled the motion of the virtual automobile using a steering wheel and foot pedals (Thrustmaster Ferrari 458 Spider).

Procedure

Each participant gave informed consent and was informed they could discontinue at any time without penalty. Following the informed consent procedure, they completed the Simulator Sickness Questionnaire, or SSQ (Kennedy, Lane, Berbaum, & Lilienthal, 1993), which allowed the experimenter to assess the initial level of symptoms (SSQ-1). Following Regan and Price (1994), pre-exposure SSQ data was used to establish a baseline against which later SSQ data could be compared. The SSQ comprises 16 symptoms, each of which is rated on a 4-point scale (not at all, mild, moderate, severe). Participants also responded to a forced-choice, yes/no question, *Are you motion sick?* Participants were instructed (both verbally and on the consent form) to discontinue the experiment immediately if they experienced any motion sickness symptoms, however mild. Participants next reported their gaming habits. It was asked whether participants currently played video games and, if so, how many hours per week. Information about participants' experience with video games is presented in Table 2-1. Information about participants' experience using HMDs is presented in Table 2-2.

Table 2-1. Experience with interactive technologies, excluding head-mounted dis- plays. Play games: do you currently play non-HMD video games? Age began: atwhat age did you begin to play non-HMD video games? Years playing: for howmany years have you played non-HMD video games? Hours/week: how many hours per week do you play non-HMD video games?

		Play Games		Age Began	Years playing	Hours/week
	n	**Yes**	**No**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
Well	45	21	24	8.36 (3.33)	9.27 (5.79)	3.09 (5.92)
Sick	34	9	25	8.32 (3.52)	8.65 (6.15)	1.01 (2.10)

Table 2-2. Experience with head-mounted displays. Used an HMD: have you everused a head-mounted displays? Own an HMD: do you own a head-mounted display system? Hours/week: how many hours per week do you currently playgames using an HMD?

		Used an HMD		Own an HMD		Hours/week
	n	**Yes**	**No**	**Yes**	**No**	**Mean (SD)**
Well	45	19	26	2	43	0.02 (0.15)
Sick	34	10	24	2	32	0.00 (0.01)

Participants next removed their shoes and were measured for height and weight, after which they stood on the force plate for approximately 2 minutes. The portion of the study associated with the force plate will be discussed in Chapter 3.

After the standing balance trials, participants sat on the stool and were shown how to adjust the Oculus Rift for comfort and visual clarity. Participants were shown the Oculus Home Screen and asked to adjust the HMD until the image was clear. Adjustments included repositioning the HMD, and changing the inter-pupillary distance. Once the participant confirmed the image was clear, the Experimenter explained the controls (for Drivers). Participants were reminded that they should discontinue immediately if they experienced any symptoms of motion sickness, however mild.

The participants played or watched game footage from a commercially available racing game, Assetto Corsa. Drivers drove a Ferrari 458 Italia on the Highlands Long Track. The course was 12 m wide, and 12 km in length. The overall shape of the course is shown in Figure 2-1. The automatic transmission option was selected. Drivers could shift into reverse (this was sometimes useful after crashes). The drivers-eye view option was selected. To increase realism, the option to include one competing car on the course was selected. The sound was played through desktop speakers.

This experiment used a between-participants, yoked control design with individual Passengers being yoked to individual Drivers. Each pair of participants was same-sex: men paired with men, and women with women. Separately for men and women, odd numbered participants were assigned to the driver group, and even-numbered participants were assigned to the Passenger group. The recording from Participant 1 was viewed by Participant 2; the recording from Participant 3 was viewed by Participant 4, and so on. Participants were reminded to discontinue immediately if they experienced any symptoms of motion sickness, however mild. Participants played or viewed the game for up to 15 minutes. Participants in the Driver group were told that, during the first 3 min of play they could ask the experimenters for clarification with the driving controls, after which they were not given any additional assistance. Data on head and torso motion were collected continuously throughout the game session; these data

Figure 2-1: Overhead representation of the racetrack. The length of the simulated track was 12.19 km.

will be reported in Chapter 4.

For Drivers who completed the 15 min session, their recorded performance was played for the corresponding Passenger until the Passenger completed the 15-min session or discontinued (whichever came first). If a Driver discontinued after at least 60 s, his or her recording was played to the corresponding Passenger. If that Passenger had not discontinued by the end of the (truncated) recording, the recording was restarted by the Experimenter, and replayed until 15 minutes were completed or until the passenger discontinued, whichever came first. Drivers who drove for less than 60 s before discontinuing were replaced, so that Passengers would view recorded driving sessions that were at least 60 s in duration.

After completing the 15-minute game exposure, or after discontinuation (whichever came first), participants completed SSQ-2, as well as the forced choice question asking them whether or not they were currently motion sick. If at SSQ-2, the participant stated they were not motion sick then they were given a printed copy of the SSQ (SSQ-3). Participants were instructed to complete this form if they began to feel motion sick at any time during the following 24 h or if they did not experience motion sickness, after 24 h. Previous research on motion sickness has shown that symptom onset may occur after the participant has left the lab (Stoffregen, 1985). Participants could return the SSQ-3 form either in person or by taking a picture of their completed form and emailing it to one of the Experimenters. If the participant did not return the SSQ-3, they were excluded from the study.

Data analysis

Following previous studies (e.g., Munafo et al., 2017; Stoffregen & Smart, 1998), participants were assigned to the Well and Sick groups based solely on their responses to the forced-choice, yes/ no question, *Are you motion sick?*, at the time of SSQ-2 or SSQ-3. For the SSQ, Total Severity Score was computed. Scores on the SSQ are not normally distributed and, for this reason, SSQ data was analyzed using nonparametric statistics, as recommended by Kennedy et al. (1993). The maximum possible Total Severity score on the SSQ was 235.62.

Repeated assessment of symptom severity could lead to inflated post-exposure severity ratings, as a function of demand character (Young, Adelstein, & Ellis, 2006; cf. Keshavarz & Hecht, 2011). However, there is no reason to expect that any effect of demand character would differ between the Well and Sick groups, given that group membership was determined solely on the basis of an independent assessment of motion sickness incidence.

For drivers, game performance was evaluated in terms of the number of laps completed, the mean driving speed (meters per second), and the mean number of crashes per lap. Laps completed and driving speed were provided by the game application. To identify crashes, experimenters reviewed recorded footage to determine the number of times the vehicle contacted the walls, or any other vehicle.

Results

Motion sickness incidence

The data are summarized in Table 2-3. The overall incidence of motion sickness was 43% (34/79). Of these, 33 stated they were motion sick at SSQ-2, and one at SSQ-3. Three participants in the Driver group discontinued after less than 60 s and therefore, as noted in the Method section, were replaced. This accounts for the fact that the dataset contains three more Drivers (41) than Passengers (38). For drivers, the incidence of motion sickness was 49% (20/41). For passengers, the incidence was 37% (14/38). These rates did not differ, $\chi 2 = 1.15$, $p > .05$. For women, the incidence of motion sickness was 44% (18/41). For men, the incidence was 42% (16/38). These rates did not differ, $\chi 2 = 0.26$, $p > .05$.

Table 2-3: Motion Sickness Incidence

	Drivers		Passengers	
	Well	**Sick**	**Well**	**Sick**
Women	11	11	12	7
Men	10	9	12	7
	21	20	24	14

Symptom severity

First, symptom severity scores were compared between groups, with separate comparisons before and after game exposure. At pre-exposure (SSQ-1), scores did not differ between the men (mean = 8.76, SD = 13.62) and women (mean = 5.84, SD = 7.94), $U = 725$, $p = .58$, between the Well (mean = 6.15, SD = 9.34) and Sick (mean = 8.69, SD = 13.01) groups, $U = 652$, $p = .24$, or between Drivers (mean = 6.66, SD = 9.33) and Passengers (mean = 7.87, SD = 12.77), $U = 738$, $p = .67$. Following game play (SSQ-2, or SSQ-3), scores did not differ between the men (mean = 38.58, SD = 30.84) and women (mean = 40.41, SD = 33.26), $U = 741.5$, $p = .71$, or between Drivers (mean = 41.51, SD = 32.90) and Passengers (mean = 37.40, SD = 31.13), $U = 726.5$, $p = .61$. However, scores were higher for the Sick group (mean = 66.60, SD = 26.33) than for the Well group (mean = 19.22, SD = 17.22), $U = 99$, $p < .001$.

Next, within groups, compared symptom severity scores before and after game exposure. Post-exposure SSQ scores were higher than pre-exposures scores for each within-group comparison. For females, pre-exposure mean = 5.84, SD = 7.93; post-exposure mean = 40.41, SD = 33.25, $Z = 4.98$, $p < .001$. For males, pre-exposure mean = 8.76, SD = 13.62; post-exposure mean = 38.58, SD = 30.84, $Z = 4.74$, $p < .001$. For Drivers, pre-exposure mean = 6.66, SD = 9.33; post-exposure mean = 41.51, SD = 32.90, $Z = 4.85$, $p < .001$. For Passengers, pre-exposure mean = 7.87, SD = 12.77; post-exposure mean = 37.4, SD = 31.13, $Z = 4.88$, $p < .001$. For Well, pre-exposure mean = 6.15, SD = 9.34; post-exposure mean = 19.12, SD = 17.22, $Z = 4.03$, $p < .001$. For Sick, pre-exposure mean = 8.69, SD = 13.01; post-exposure mean = 66.55, SD = 26.33, $Z = 5.09$, $p < .001$.

Discontinuation

Twenty-nine participants discontinued without completing the 15-minute game exposure. Each of these participants stated that they were motion sick and gave motion sickness as their reason for discontinuation. That is, each participant who discontinued without completing the 15-minute game exposure was assigned to the Sick group. Of the 29 participants who discontinued, 16 were women, and 13 were men, while 16 were Drivers, and 13 were Passengers. The overall mean time of discontinuation was 360 s (SD = 226.51). The Sex × Driving status interaction was significant, $F(1, 25) = 4.71$, $p = .04$, partial $\eta 2 = 0.158$ (Figure 2-2). The 95% confidence intervals revealed that, among Drivers, women (mean = 191.3 s, SD = 68.2 s; 95% CI = 50.9–331.8 s) discontinued earlier than men (mean = 457.7 s, SD = 77.3 s; 95% CI = 297.4–615.9 s). For Passengers, the difference between men and women was not significant.

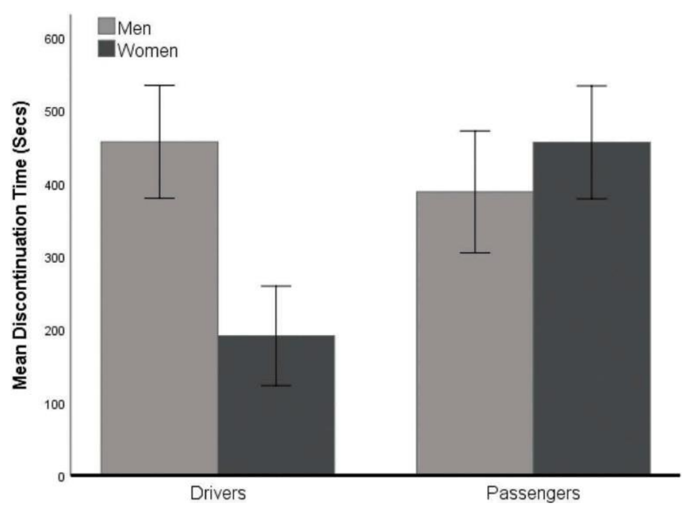

Figure 2-2: Mean time of discontinuation for the 29 participants who did not complete the 15-minute game exposure, illustrating the statistically significant Sex × Driving Status interaction. The error bars represent the standard error of the mean.

Looping of footage

For drivers that discontinued before 15 minutes, their gameplay was replayed until 15 minutes was reached or until the passenger discontinued; thus, some passengers were exposed to repetition of the driver's footage. To ensure this was not a confounding variable, incidence among passengers that saw looped footage to those that did not was compared. Among passengers who saw repeated footage, 36.4% stated they were sick, while among passengers who did not see repeated footage, 37.0% stated they were sick.

Game performance

For participants in the driver group, game performance was evaluated in terms of the number of laps completed, the mean number of crashes per lap, and mean driving speed. The number of laps completed differed between men (mean = 1.79, SD = 0.86) and women (mean = 1.14, SD = 0.94), $U = 137$, $p = .045$, and between the Well (mean = 2.10, SD = 0.44) and Sick (mean = 0.75, SD = 0.85) groups, $U = 42.50$, $p < .001$. The number of crashes per lap did not differ between men (mean = 14.08, SD = 8.70) and women (mean = 13.02, SD = 12.42), $U = 173$, $p = .35$, or between the Well (mean = 16.25, SD = 10.90) and Sick (mean = 10.64, SD = 10.03) groups, $U = 137$, $p = .06$.

The mean driving speed for laps completed was found to be normally distributed; thus, an independent-sample t-test was performed. A significant difference was found between women (mean = 32.74 m/s, SD = 4.34) and men (mean = 36.86 m/s, SD = 4.89), $t(30) = 2.484$, $p = .019$. The difference between the Well (mean = 35.49, SD = 4.84) and Sick (mean = 34.24, SD = 5.52) groups was not significant, $t(30) = 0.66$, $p = .514$.

Discussion

Participants were exposed to a driving video game presented via an HMD. The maximum exposure was 15 minutes. In a yoked-control design, half the participants controlled the virtual vehicle (Drivers), while half viewed drivers' recorded sessions (Passengers). Equal numbers of men and women were assigned to the driver and passenger groups. After game exposure, the incidence of motion sickness was 43%. The incidence of motion sickness did not differ between drivers and passengers, or between women and men. At post-exposure, the severity of motion sickness symptoms did not differ between women and men, or between drivers and passengers. Of the 34 participants in the Sick group, 29 discontinued game exposure without completing the 15-minute session. Of these 29, among Sick Passengers, the time of discontinuation did not differ between women and men. However, among Sick Drivers, women discontinued significantly earlier than men. These results are discussed in turn.

Motion sickness in head-mounted displays

The overall incidence of motion sickness was similar to other studies with video games (e.g., Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008), virtual driving (Dong et al., 2011), and HMDs (Merhi et al., 2007; Munafo et al., 2017), as well as to virtual environments presented via video projection (Villard, Flanagan, Albanese, & Stoffregen, 2008). Symptom severity also was comparable to previous studies. The experimenter concludes that the nauseogenic properties of the driving game were representative of virtual environments, video games, and HMDs.

For participants in the Sick group, post-exposure ratings of symptom severity (SSQ scores) were greater than preexposure scores, as expected. However, this study also found that post-exposure scores were greater than pre-exposure scores among participants in the Well group. This finding, which is common (e.g., Li et al., 2018; Munafo et al., 2017; Walter et al., 2019) underscores the logical distinction between the incidence of motion sickness (a yes/no dichotomy) and the severity of symptoms (a continuum). The distinction is important, also, because virtual reality systems, in general, and HMDs, in particular, are associated with an increase in certain symptoms, such as headache and eyestrain, among people who expressly deny being motion sick (e.g., Munafo et al., 2017; Stanney & Hash, 1998).

Among participants in the passenger group, exposure to repeated (looped) footage did not affect the likelihood of motion sickness.

The driver-passenger effect

The classic driver-passenger effect was not replicated; that is, this study found no evidence that passengers were more likely than drivers to report motion sickness. However, this study did find that the overall incidence of motion sickness was representative of other studies of visually induced motion sickness. The representativeness of the overall sickness incidence and severity, coupled with the robustness of the driver-passenger effect in both physical (Rolnick & Lubow, 1991) and virtual driving (Dong et al., 2011) settings, lend credence to the idea that the present null result may constitute a novel effect. That is, it may be that the actual risk of motion sickness for drivers and passengers is equal in the context of HMDs. That being said, it always is difficult to interpret null effects, and future research is needed before such a conclusion could be reached.

It has been suggested that motion sickness in closed-loop virtual environments may be related to computational time lags between control inputs (e.g., head movements, in an HMD) and display outputs. However, controlled manipulations of time lag in experimental research have provided only mixed support for this hypothesis (e.g., Draper et al., 2001; Palmisano, Mursic, & Kim, 2017). Moreover, time lags in current iterations of HMD systems can be extremely short (Feng, Kim, Luu, & Palmisano, 2019). In the present chapter, time lag could have influenced motion sickness among drivers, but not among passengers. The fact that this study found no differences in motion sickness incidence or severity between drivers and passengers provides no support for the hypothesis that time lag is an etiological factor for motion sickness in closed-loop VR systems.

It is widely argued that the subjective experience of self-motion (i.e., vection) may be causally related to visually induced motion sickness (e.g., Hettinger & Riccio, 1992). Kim, Chung, Nakamura, Palmisano, and Khuu (2015) examined vection among users of an HMD. They found that reported vection strength was greater when participants were passive viewers of virtual self-motion than when they actively controlled virtual self-motion. In the present chapter, the experimenter did not measure vection. However, if it is assumed that the effect reported by Kim et al., would have occurred, then vection should have been stronger among participants in the Passenger group than among participants in the Driver group. These findings suggest that the incidence and severity of motion sickness did not differ between these groups are not consistent with the hypothesis that vection is causally related to visually induced motion sickness.

Sex differences

The classic sex difference in motion sickness was not replicated; that is, this study found no evidence that women were more likely than men to become motion sick. Similarly, this study found no evidence that women’s symptom severity ratings were higher than men’s symptom severity ratings. Munafo et al. (2017) studied motion sickness among HMD users. They found a sex difference in motion sickness incidence during an ambulation game (Experiment 2), but they found no sex difference when participants played a game that did not include locomotion (Experiment 1). It may be that, in the context of HMDs, sex differences in motion sickness incidence are related primarily to the control of ambulation. Clifton and Palmisano (2019) evaluated motion sickness among HMD users who controlled virtual ambulation, and also found no sex differences. It would be interesting, in future research with HMDs, directly to compare motion sickness among women and men in games featuring virtual ambulation and virtual driving.

In terms of motion sickness incidence and symptom severity, this study found no evidence for the existence of sex differences in the driver-passenger effect. However, among those participants who discontinued early (all of whom stated they were motion sick), this study found that the time of discontinuation (that is, the duration of exposure to the game) was influenced by a statistically significant interaction between sex and driver/passenger status (Figure 2-2). Among passengers, discontinuation time did not differ between the sexes, but among drivers, women discontinued earlier than men. This effect appears to be the first evidence that the driver-passenger effect can differ between the sexes. This effect, while modest, motivates future research. Perhaps the most obvious study motivated by the present results would be to evaluate possible sex differences in the driver-passenger effect in physical vehicles. This approach might be achieved using automobiles, or using laboratory whole-body motion devices, similar to Rolnick and Lubow (1991). Another approach might be to conduct a survey of a large sample of adults, specifically posing questions about experiences with “car sickness” as drivers, and as passengers, while requesting that respondents indicate their sex. Existing motion history questionnaires might be adapted to facilitate such a study (e.g., Golding, 2006).

Limitations

There are two principal limitations of this study. The first concern is the use of HMDs. It cannot be assumed that effects observed in the present study would generalize to other types of virtual environment systems, such as desktop displays, or projection displays. Future research is needed to address these issues. For example, the current study could be replicated using a console video game, rather than an HMD (cf., Dong et al., 2011).

It is equally important to acknowledge that while motion sickness is rare among drivers in physical driving, it is common among drivers in virtual driving, as occurs in driving video games (e.g., Chang et al., 2017; Dong et al., 2011; Nickkar, Jeihani, & Sahebi, 2019; Stoffregen et al., 2017), and in flight simulators (e.g., Stoffregen, Hettinger, Haas, Roe, & Smart, 2000). Motion sickness among drivers of virtual vehicles appears to be part of the larger problem of motion sickness associated with all forms of virtual locomotion (e.g., Chen et al., 2012; Munafo et al., 2017; Stoffregen et al., 2014).

Conclusion

In this present chapter, the influence of sex susceptibility and vehicle control on motion sickness was examined. In previous motion sickness research, it has been shown that women are more susceptible than men at becoming motion sick during VR exposure (Munafo et al., 2017). Additionally, prior research has shown that participants that are in control of either a physical (Rolnick & Lubow, 1991), or a virtual vehicle (Dong et al., 2011) are less likely to report motion sickness than those that are not in control. In terms of motion sickness incidence, this study found no differences between males and females or between driving and passenger groups. Nevertheless, for drivers that discontinued early because of motion sickness, females had less VR exposure time than males. This difference between males and females suggests that sex differences in motion sickness may be dependent on the task being performed in the virtual environment. Future work is needed to better understand these specific tasks, thereby allowing mitigation approaches to be explored.

Chapter 3: Postural precursors of motion sickness in head-mounted displays: drivers and passengers, women and men

Introduction

Motion sickness is preceded by distinctive patterns of postural sway. That is, postural sway differs between persons who (later) report motion sickness, and those who do not. Such differences have been identified in postural sway during exposure to potentially nauseogenic motion stimulation (e.g. Bonnet et al. 2006; Stoffregen and Smart 1998). More relevant for the present study is the finding of such differences in postural sway before participants were exposed to stimulus motion of any kind (e.g. Arcioni et al. 2019; Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016; Palmisano, Arcioni, and Stapley 2018; Risi and Palmisano 2019; Stoffregen et al. 2013; Stoffregen et al. 2000; Stoffregen and Smart 1998; Stoffregen et al. 2010). In the present chapter, it is asked how postural precursors of motion sickness might be influenced by co-variation of an intrinsic factor (sex) and an extrinsic factor (control of a virtual vehicle).

Sex-specific postural precursors of motion sickness

Susceptibility to motion sickness differs between women and men. This is true (e.g. Lawther and Griffin, 1986), and in cases of virtual displacement, such as interactive video games (e.g. Munafo et al. 2016). Interestingly, there also are characteristic sex differences in the quantitative kinematics of body sway (e.g. Anton, Ernst, and Basta 2019; Era et al. 2006; Kim et al. 2010). Taken together, these literatures suggest the possibility that sex differences in susceptibility to motion sickness might be related to sex differences in the control of the body. Recent evidence is consistent with this idea.

Koslucher, Haaland, and Stoffregen (2016) exposed standing participants to imposed oscillation of the illuminated environment (a moving room). Motion sickness incidence was greater among women (38%) than among men (9%). Prior to movement of the room, the researchers measured standing body sway (on a force plate) in the absence of any motion stimuli, while participants performed one of two simple visual tasks. Analysis of the positional variability of the body's center of pressure revealed a statistically significant interaction between sex, the two visual tasks, and later membership in the Well and Sick groups.

Munafo et al. (2016) conducted a similar evaluation of pre-exposure body sway during performance of simple visual tasks. However, in their study, measurement of body sway was followed by exposure to an interactive (i.e. user-controlled) video game presented via a head-mounted display. When the video game included virtual locomotion (their Experiment 2), the incidence of motion sickness was greater among women (78%) than among men (33%). Analysis of positional variability of the center of pressure during pre-exposure stance again revealed a statistically significant, 3-way interaction between sex, visual tasks, and later membership in the Well and Sick groups.

Sex differences in postural precursors of motion sickness have not been incremental. Rather, in both the studies of Koslucher, Haaland, and Stoffregen (2016) and

Munafo et al. (2016), male and female postural precursors of motion sickness differed qualitatively.

Postural precursors and the driver-passenger effect

In automobiles, motion sickness is more common among passengers than among drivers. This common anecdotal report has been verified in controlled laboratory research using purpose-built whole-body motion devices (e.g. Rolnick and Lubow 1991). The same effect occurs in the context of virtual motion: In Dong, Yoshida, and Stoffregen (2011), seated participants either controlled (drivers) or merely watched (passengers) a driving video game. By a factor of four, the incidence of motion sickness was greater among passengers.

Dong, Yoshida, and Stoffregen (2011) monitored the kinematics of the head and torso during exposure to the driving game. Analyses of these data revealed postural precursors of motion sickness for both drivers and passengers. In addition, Dong, Yoshida, and Stoffregen (2011) found that movement of the head and torso differed between drivers and passengers. The temporal dynamics of head and torso movement differed between drivers and passengers. Perhaps surprisingly, despite the finding that motion sickness was more common among passengers than among drivers, analysis of the spatial magnitude of movement revealed that drivers moved more than passengers.

Focus of This Chapter

Chapter 2 introduced a study of motion sickness among participants exposed to a driving video game presented through a head-mounted display. Using the yoked-control method of Dong, Yoshida, and Stoffregen (2011), half of participants (Drivers) controlled the virtual vehicle, while the other half (Passengers) did not control the virtual vehicle. This manipulation was crossed with an equal variation in sex: Half of both the Driver and Passenger groups were women, while the other half were men. The overall incidence of motion sickness was comparable to previous studies (e.g. Munafo et al. 2016). Chapter 2 found no differences in motion sickness incidence or severity between the sexes, or between drivers and passengers (for interpretation of these potentially anomalous findings, see Chapter 2). The data reported in Chapter 2 were part of a larger study of sex differences and the driver-passenger effect in head-mounted displays. In the present chapter, data on postural sway and visual performance that were collected from the same participants, as part of that larger study is reported.

Previous research has demonstrated that postural precursors of motion sickness differ between women and men (Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016). In this chapter, it is asked whether sex-specific postural precursors of motion sickness might, themselves differ between drivers and passengers in driving games presented via a head-mounted display system.

Historically, human movement has often been evaluated in terms of spatial magnitude (e.g. the standard deviation of position, of the length, or area of postural sway). Such measures commonly lead to definitions of movement stability in which greater magnitude is equated with less stability (e.g. Reed-Jones et al. 2008). Dynamic systems theory has motivated a qualitative shift in measures of animate movement, and in concepts of stability and instability of movement (e.g. Stergiou and Decker 2011). Measures of the temporal dynamics of movement differ qualitatively from measures of spatial magnitude (e.g. Lin et al. 2008; Riccio and Stoffregen 1988). Postural precursors of motion sickness can exist in the temporal dynamics of sway (e.g. Stoffregen et al. 2010), as well as in its spatial magnitude (e.g. Stoffregen and Smart 1998), and the degree of multifractality of the postural time series (e.g. Koslucher, Munafo, and Stoffregen 2016; Munafo et al. 2016). In this chapter, two orthogonal measures of standing body sway are evaluated. The spatial magnitude of sway in terms of the positional variability of the body is evaluated (e.g. Bonnet et al. 2006; Stoffregen et al. 2013).

The degree of multifractality in sway is evaluated. The analysis of multifractality in human movement is relatively novel, and researchers have stated it is not entirely clear how variations in multifractality should be interpreted (Kelty-Stephen et al. 2013). More broadly, there is ongoing debate about the nature of stability and instability in animate movement (e.g. Riccio 1993; Stergiou and Decker 2011). The postural instability theory (Riccio and Stoffregen 1988) can help interpret multifractality in postural sway. Postural instability theory dictates that patterns of sway among participants who will become sick are less stable; hence, differences in multifractality between the Well and Sick groups correspond to variations in postural stability. Koslucher, Munafo, and Stoffregen (2016) and Li et al. (2018), found that motion sickness was preceded by variations in multifractality that were not observed among participants who did not become sick. In this chapter, it is asked whether differences between Well and Sick participants in the multifractality of standing body sway might be modulated by sex, and/or by participants' status as Drivers versus Passengers during subsequent exposure to a virtual vehicle.

Method

Participants

A total of 79 individuals participated (41 women and 38 men), in exchange for course credit. Participants ranged in age from 18 to 49 years (mean = 21.84 years, SD = 4.19 years), in height from 1.51 to 1.94 m (mean = 1.72 m, SD = 0.10 m), and in weight from 47.63 to 104.33 kg (mean = 71.58 kg, SD = 12.47 kg). The research protocol was approved in advance by the IRB of the University of Minnesota.

Apparatus

This study used the Oculus Rift CV1. The device comprised a lightweight (0.360 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with 1080 × 1020 resolution, yielding a 100° horizontal field of view. A lens located in front of each display rendered display content at optical infinity.

Data on postural activity were obtained using a force plate (AccuSway Plus; AMTI, Watertown, MA). The displacement of the center of pressure (COP) in the anterior-posterior (AP) and mediolateral (ML) axes was collected at 50 Hz.

Procedure

Each participant gave informed consent and was informed they could discontinue at any time without penalty. Following previous studies (e.g. Dong, Yoshida, and

Stoffregen 2011; Koslucher et al. 2015; Merhi et al. 2007; Stoffregen et al. 2008, 2010; Stoffregen and Smart 1998), the incidence of motion sickness and the severity of symptoms was separately assessed (for details, see Chapter 2). Participants were instructed (both verbally and on the consent form) to discontinue the experiment immediately if they experienced any motion sickness symptoms, however mild.

For postural testing, participants removed their shoes and were measured for height and weight, after which they stood on the force plate, which was located 1 m from a wall. Participants stood on marked lines on the plate such that their heels were 17 cm apart with an angle of 10° between the feet. While standing on the force plate, each participant completed a single trial in an Inspection task and one in a Search task. The visual tasks were similar to those used by Munafo et al. (2016), and Stoffregen et al. (2000). Targets consisted of sheets of white paper 21.6 cm × 27.9 cm, mounted on rigid cardboard. Targets for the Inspection and Search tasks were 1.0 m in front of the heels, affixed to a white wall and adjusted to each participant's eye height. In the Inspection task, the target was a blank sheet of white paper. There was not a single fixation point: Participants were instructed to keep their gaze within the boundary of the target. In the Search task, the target was a block of English text, comprising 14 lines of text printed in a 12-point sans serif font, which was affixed to an otherwise blank card. In the Search task, the participant was asked to count the number of times the letter, r, appeared in the block of text. At the end of each Search trial, the participant reported the number of letters counted and their position in the text at the end of the trial. Each trial was 60 s in duration. The Inspection and Search tasks were presented in alternating order. Odd-numbered participants began with the Search task, while even-numbered participants began with the Inspection task.

After performing the visual tasks while standing, participants sat on the stool, donned the Oculus headset, and were exposed to Assetto Corsa, a commercial driving game. Each Driver drove a Ferrari 458 Italia on the Highlands Long Track. Details of the driving game were reported in Chapter 2. During exposure to the video game, a between-participants was used, yoked control design, with individual Passengers yoked to individual Drivers. Participants played or viewed the game for up to 15 min. Data on head and torso motion were collected continuously throughout the game session; these data will be discussed in Chapter 4. Additional details of the yoked-control procedure are reported in Chapter 2.

After completing the 15-min game exposure, or after discontinuation (whichever came first), motion sickness incidence and severity was assessed.

Analysis of postural sway

The spatial magnitude and multifractality of center of pressure positions was separately evaluated. The spatial magnitude of postural activity in terms of positional variability was evaluated, which was defined operationally as the standard deviation of center of pressure positions. The multifractality of postural activity using multifractal detrended fluctuation analysis was evaluated, MF-DFA (e.g. Ihlen et al. 2013; Munafo et al. 2016). MF-DFA is an extension of more traditional detrended fluctuation analysis, or DFA (Lin et al. 2008). MF-DFA has been used in the assessment of postural sway in a variety of contexts (e.g. Fink et al. 2019; Munafo et al. 2016). Traditional DFA assumes that fluctuations in a time series are homogeneous (Ihlen and Vereijken 2010). Multifractal fluctuations are interdependent and heterogeneous. The range of the singularity exponent, *h(q)*, indicates the heterogeneous nature of multifractal fluctuations (Ihlen 2012). The width of this range can be used as an index of the degree (or amount) of multifractality in a time series. The range of *h(q)* values is known as the *singularity spectrum*, or simply the *spectrum*. The wider the multifractal spectrum, the more multifractal is the movement (Kelty-Stephen et al. 2013). Inferential statistics on the width of the singularity spectrum was conducted for each trial. MF-DFA was conducted using open source code for MATLAB (MFDFA1; Ihlen 2012). A minimum scaling range of 16 data points with 19 evenly spaced increasing segment sizes to a maximum of the length of the time series was selected. This range was the same for each time series. Use of the range of *h(q)* to estimate spectrum width is susceptible to outliers (Ihlen 2012; cf. Kelty-Stephen et al. 2013). For this reason, before conducting ANOVA on spectrum width the experimenter removed data from participants for whom spectrum width was greater than three standard deviations from the overall mean (across trials and participants).

There were 3000 data points in each time series. Separate ANOVAs on positional variability and the width of the multifractal spectrum was conducted. For each ANOVA, the factors were Body Axis (AP vs. ML), Visual Task (Inspection vs. Search), Sex (Women vs. Men), Control (Drivers vs. Passengers), and Sickness Groups (Well vs.

Sick). Body Axis and Visual Task were within-participants factors, while Sex, Control, and Sickness Groups was a between-participants factor.

Results

As reported by Chapter 2, the overall incidence of motion sickness was 43% (34/79). Motion sickness incidence did not differ between Drivers and Passengers, or between women and men. Data on exposure duration (i.e. time of discontinuation) and symptom severity were reported in Chapter 2.

Search task performance

Before exposure to the head-mounted display, standing participants performed the Inspection and Search tasks. Performance on the Inspection task was not evaluated. Following previous studies (e.g. Koslucher, Haaland, and Stoffregen 2016; Stoffregen et al. 2000), it was assumed that participants were able to maintain their gaze within the borders of the card. Performance on the Search Task was evaluated in terms of percent correct, which was computed as the number of times the target letter was counted divided by the total number of target letters in the stimulus text, and by reading speed, which was computed as the number of words counted during the trial divided by the duration of the trial. Overall, participants counted 72.63% ($SD = 0.18$) of the target letters. Independent sample t-tests were used to evaluate differences in reading accuracy between the sexes, between Drivers and Passengers, and between the Well and Sick groups. There were no significant effects.

Reading speed was evaluated using a 2 (Women vs. Men) × 2 (Driver vs. Passenger) × 2 (Well vs. Sick) ANOVA. The Sex Driver-Passenger interaction was significant, $F(1, 71) = 9.24$, $p = .003$, partial $\eta 2 = .115$ (Figure 3-1). Post-hoc tests (95% confidence intervals) revealed that reading speed differed between Drivers and Passengers for men, but not for women.

Positional variability

For the positional variability of the center of pressure, the main effect of Body Axis was significant, $F(1, 71) = 216.47$, $p < .001$, partial $\eta 2 = .75$. Positional variability in the AP axis (mean = 0.390 cm, SE = 0.018 cm) was greater than in the ML axis (mean = 0.174 cm, SE = 0.010 cm). In addition, the main effect of Visual Task was significant, $F(1, 71) = 4.38$, $p = .04$, partial $\eta 2 = .06$. Positional variability during performance of the Inspection task (mean = 0.303 cm, SE = 0.020 cm) was greater than during performance of the Search task (mean = 0.261 cm, SE = 0.01 cm). Finally, the Body Axis × Visual Task interaction was significant, $F(1, 71) = 6.03$, $p = .016$, partial $\eta 2 = .08$ (Figure 3-2). There were no other significant effects.

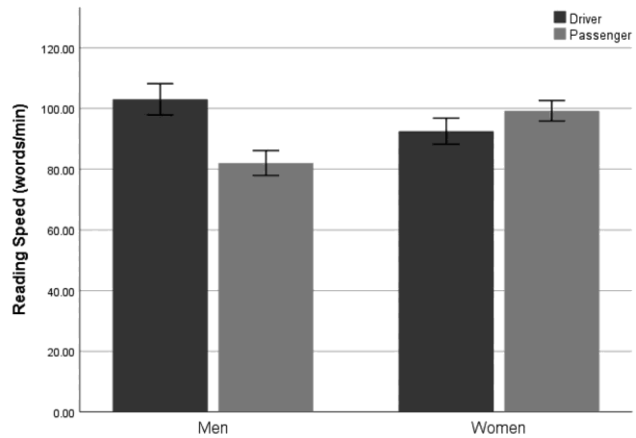

Figure 3-1: Reading speed (words/min) during performance of the Search task, illustrating the statistically significant interactionbetween sex and vehicle control. The error bars represent onestandard error of the mean.

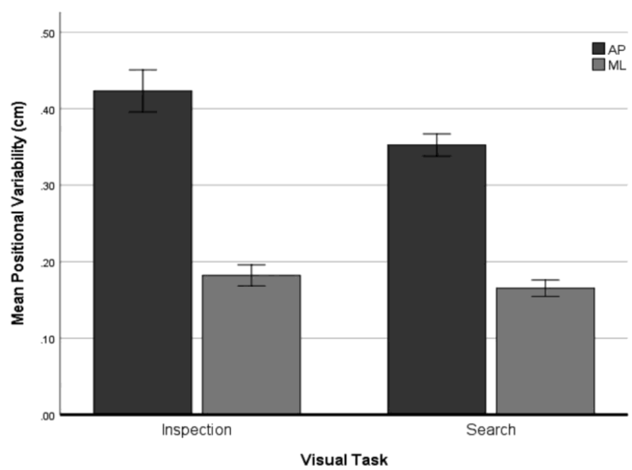

Figure 3-2: Positional variability of the Center of Pressure, illustrating the statistically significant interaction between Body Axis(AP vs. ML) and Visual Task (Inspection vs. Search). The error bars represent one standard error of the mean.

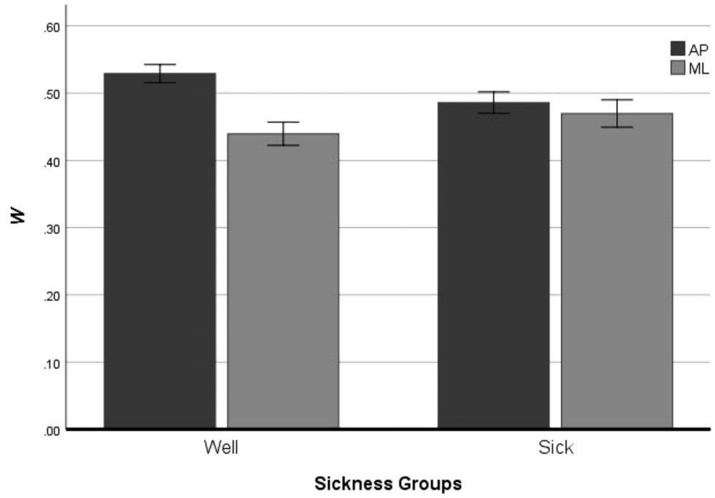

Figure 3-3: Width, W, of the multifractal spectrum, illustrating the statistically significant interaction between Body Axis (AP vs. ML) and Sickness Groups (Well vs. Sick). The error bars represent one standard error of the mean.

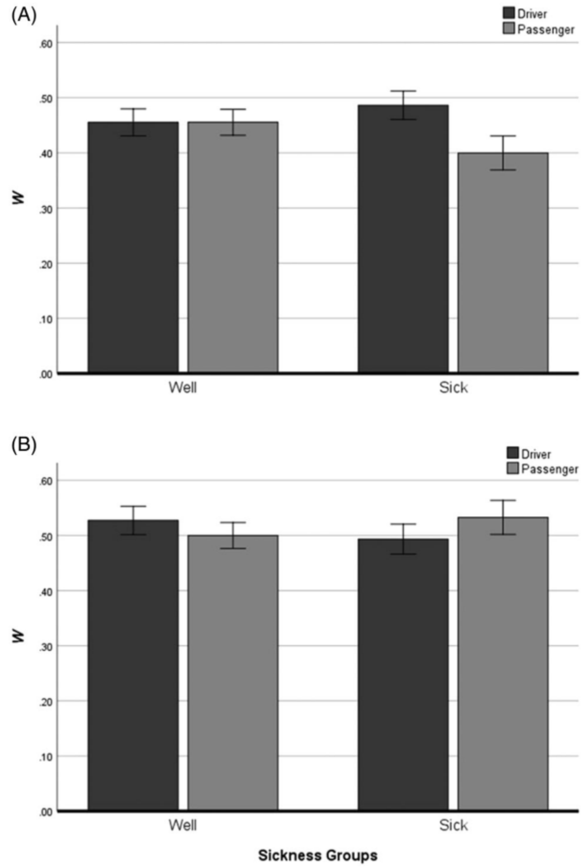

Figure 3-4: Width, W, of the multifractal spectrum, illustrating the statistically significant interaction between Vehicle Control (Drivers vs. Passengers), Sex (Women vs. Men) and Sickness Groups (Well vs. Sick). (A) Women; (B) men. The error bars represent the standard error of the mean.

Width of the multifractal spectrum

One participant was identified as an outlier, and so was excluded from the analysis of the width of the multifractal spectrum. The main effect of Body Axis was significant, $F(1, 70) = 12.96$, $p = .001$, partial $\eta 2 = .16$. The multifractal spectrum was wider for postural activity in the AP axis (mean = 0.51, SE = 0.01) than in the ML axis (mean = 0.46, SE = 0.01). The main effect of Visual Tasks was significant, $F(1, 70) = 17.63$, $p < .001$, partial $\eta 2 = .20$. The multifractal spectrum was wider for postural activity during performance of the Inspection task (mean = 0.52, SE = 0.01) than during performance of the Search task (mean = 0.45, SE = 0.01). The main effect of Sex was significant, $F(1, 70) = 11.56$, $p = .001$ partial $\eta 2 = .142$. The multifractal spectrum was wider for the postural activity of men (mean = 0.51, SE = 0.01) than women (mean = 0.45, SE = 0.01). The interaction between Body Axis and Sickness Groups was significant, $F(1, 70) = 6.19$, $p = .015$, partial $\eta 2 = .08$ (Figure 3-3). The 95% confidence intervals revealed that the difference between the AP and ML axes was significant for the Well group (AP Mean = 0.52, SD = 0.1, 95% CI [0.50–0.56]; ML Mean = 0.44, SD = 0.02, 95% CI [0.41–0.47]), but not for the Sick group. Finally, the Sex × Sickness Groups × Control interaction was significant, $F(1, 70) = 4.14$, $p = .046$, partial $\eta 2 = .05$ (Figure 3-4). The 95% confidence intervals revealed that for sick women, Drivers (mean = 0.486, SD = 0.03, 95% CI [0.44–0.54]) and Passengers (mean = 0.40, SD = 0.03, 95% CI [0.34–0.46]) differed. In addition, for sick female passengers, spectrum width was reduced relative to well male drivers (mean = 0.53, SD = 0.03, 95% CI [0.48–0.58]) and sick male passengers (mean = 0.53, SD = 0.03, 95% CI [0.47–0.59]). In addition, for sick male Passengers (mean = 0.53, SD = 0.03, 95% CI [0.47–0.59]) spectrum width differed from well female Drivers (mean = 0.46, SD = 0.03, 95% CI [0.41–0.50]) and well female Passengers (mean = 0.46, SD = 0.02, 95% CI [0.41–0.50]). There were no other significant effects.

Discussion

Standing body sway was monitored as participants performed simple visual tasks, in one of which participants counted designated target letters in a block of text. After completion of the standing visual tasks, participants were exposed to a virtual driving game presented via a head-mounted display. In a yoked-control design, half the participants drove the virtual vehicle (Drivers), while the other half merely watched prerecorded vehicle motion (Passengers). Drivers and Passengers were evenly divided between women and men. In the letter counting task, reading speed differed between women and men as a function of their future status as Drivers or Passengers. As reported in Chapter 2, exposure to the virtual vehicle led to motion sickness in some participants. Standing body sway was evaluated for differences between Drivers and Passengers, women and men, and Well and Sick groups. Common effects of visual tasks on the kinematics of standing body sway was replicated, and confirmed that sway differed between the sexes. In addition, statistically significant differences between the Well and Sick groups was identified. Because data on standing body sway were collected before participants were exposed to the virtual vehicle, these interactions reveal postural precursors of visually induced motion sickness. These results are discussed in turn.

Reading speed

While standing, participants performed the Inspection and Search tasks. Several studies have shown that postural activity differs during performance of these two visual tasks (Stoffregen et al. 2000). The primary purpose in assessing performance on the Search tasks was to verify that participants actually performed the tasks. Previous studies of postural precursors of motion sickness have assessed postural activity during performance of the same Inspection and Search tasks. This manipulation sometimes has revealed sex differences in visual performance. For example, Koslucher, Haaland, and

Stoffregen (2016), found that women read more rapidly than men. In this chapter, it was found that sex differences in reading speed differed between participants assigned to the Driver versus Passenger groups (Figure 3-1). The 95% confidence intervals revealed that reading speed differed between Drivers and Passengers among men, but not among women. One way to interpret this effect is that overall between-participants reading speed was more variable among men than women. Sex differences have been reported in several cognitive abilities, such as verbal and quantitative reasoning. Interestingly, while researchers have found sex differences in mean scores, in some cases they also have found statistically significant sex differences in the between-participants variability of scores, with variability being greater among males than females (e.g. Strand, Deary, and Smith 2006). The present result is consistent with such effects.

Postural effects independent of motion sickness

Several statistically significant effects were identified in postural activity that were independent of motion sickness status. While not relevant to the existence of postural precursors of motion sickness, these effects, as replications, are important as validity checks for the experimenter's manipulations. The main effects of body axis, in both positional variability and the width of the multifractal spectrum, replicated a common finding (e.g. Balasubramaniam, Riley, and Turvey 2000; Munafo et al. 2016; Winter et al. 1996). Similarly, the main effects of visual tasks, in both positional variability and the width of the multifractal spectrum also replicated a common finding (e.g. Koslucher et al. 2012; Prado, Stoffregen, and Duarte 2007; Stoffregen et al. 2000; Yu et al. 2013). For positional variability, the interaction between these factors (Figure

3-2) reflected the fact that the Search task constrained postural sway more in the AP axis than in the ML axis, as has been reported in previous studies (e.g. Izquierdo-Herrera et al. 2018; Koslucher et al. 2012). Many studies have reported that the kinematics of standing body sway differ between the sexes. In previous research, sex differences have been observed in both the spatial magnitude and the temporal dynamics of standing body sway (e.g. Era et al. 2006; Kim et al. 2010). The current finding of a sex difference in the width of the multifractal spectrum appears to be novel.

Taken together, several statistically significant effects that were independent of the occurrence of motion sickness were observed. Each of these effects replicated effects observed in previous studies conducted in different laboratories using a wide range of specific manipulations and dependent variables. Accordingly, this replication of these effects suggests that the sample was representative, and that the manipulations were compatible with the existing literature.

Postural precursors of motion sickness

In evaluating sway before participants were exposed to any stimulus motion, this chapter found no evidence for postural precursors of motion sickness in the positional variability of the COP. Researchers often have found postural precursors of motion sickness in measures of the spatial magnitude of postural sway, such as positional variability (e.g. Arcioni et al. 2019; Koslucher et al. 2014; Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016; Palmisano, Arcioni, and Stapley 2018; Stoffregen and Smart 1998; Villard et al. 2008; Weech, Varghese, and Barnett-Cowan 2018).

However, some studies have not found postural precursors of motion sickness in measures of the spatial magnitude of sway (e.g. Dennison and D’Zmura 2017; Li et al. 2018; Palmisano, Arcioni, and Stapley 2018; Stoffregen et al. 2013). The postural instability theory of motion sickness (Riccio and Stoffregen 1988) predicts that postural precursors of motion sickness will exist; however, Riccio and Stoffregen stated explicitly that these precursors need not exist in measures of the spatial magnitude of sway, such as the positional variability of the COP. Contrary to subsequent mis-interpretations (e.g., Dennison and D’Zmura 2017), Riccio and Stoffregen did not define stability and instability solely in terms of the spatial magnitude of movement. That is, they did not predict that individuals who later became motion sick would sway *more* than individuals who did not become sick. Consistent with this position of Palmisano et al. (2018, 326) noted, ‘it is possible then that reanalysis of this postural data using … non-linear analyses … might uncover relationships that would not otherwise be observable’. It is in part for this reason that multiple, orthogonal measures of postural sway were evaluated.

For the width of the multifractal spectrum, two interactions that included the Sickness Groups variable were found. First, the interaction between Sickness Groups and Body Axis was statistically significant (Figure 3-3). The 95% confidence intervals revealed that spectrum width differed between the AP and ML axes for the Well group, but not for the Sick group. That is, the variation between body axes that characterized postural sway in the Well group was absent among those who (later) reported motion sickness. The absence of axis-specific multifractality can be interpreted as an absence of axis-specific control of posture (e.g. Balasubramaniam, Riley, and Turvey 2000). If axis-specific control characterizes stable control of posture, then the absence of axis-specific control can be interpreted as a form of unstable control, consistent with the postural instability theory of motion sickness.

This study also found a statistically significant 3-way interaction between sex, driving status, and sickness groups (Figure 3-4). That is, postural precursors of motion sickness differed between the sexes as a function of their future role in the video game; active control (Drivers) versus passive observation (Passengers) of the motion of a virtual vehicle. These results support the hypothesis that the postural precursors of motion sickness may be unique to each individual (e.g. men vs. women) and may vary with changes in task dynamics (e.g. driver vs. passenger); (cf. Slowinski et al. 2016).

The identification of postural precursors of motion sickness before participants were exposed to any stimulus motion is consistent with previous studies in which postural precursors of motion sickness have been identified prior to sea travel (Stoffregen et al. 2013), and before exposure to laboratory motion devices (e.g. Palmisano, Arcioni, and Stapley 2018; Stoffregen and Smart 1998), and head-mounted displays (Arcioni et al. 2019; Munafo et al. 2016; Risi and Palmisano 2019). The finding that sway differed between participants as a function of their subsequent role in the experiment (Drivers vs. Passengers) is novel. The effect might be regarded as a spurious result of random assignment. However, the effect also could reflect actual variations arising from long-term experience. Stoffregen et al. (2017) evaluated postural precursors of motion sickness while driving a virtual vehicle. They compared middle-aged adults with versus without decades of experience driving physical vehicles. While driving a virtual vehicle, postural precursors of motion sickness differed between participants as a function of whether they had experience driving physical vehicles. Stoffregen et al. interpreted this effect as reflecting constraints on control of the body (within physical vehicles) that differ between drivers and passengers. The effect reported by Stoffregen et al. together with the effect illustrated in Figure 3-4 may be related to the developing consensus that the definition of postural activity is not general, or context-independent, but varies across tasks and situations (e.g., Haddad et al. 2013; Riccio and Stoffregen 1988).

Conclusion

Standing body sway before participants were exposed to a virtual vehicle presented via a head-mounted display was evaluated. During stance, the multifractality of sway differed between participants who (later) became sick and those who did not. This study found that postural precursors of motion sickness were influenced by the co-variation of an intrinsic factor (sex) and an extrinsic factor (control of a virtual vehicle). These results are consistent with the general prediction of the postural instability theory of motion sickness (Riccio and Stoffregen 1988) that the kinematics of movement should differ between individuals who become motion sick and those who do not, and that differences in movement should exist before the onset of subjective symptoms. The effects that are observed in this study are consistent with effects reported in the context of sex (e.g. Koslucher, Haaland, and Stoffregen 2016), and in research comparing individuals with versus without experience controlling physical vehicles (Chang et al. 2017; Stoffregen et al. 2017). Overall, the results are consistent with the postural instability theory of motion sickness, and indicate that postural precursors of motion sickness can be influenced by both intrinsic and extrinsic factors.

Chapter 4: Postural Activity During Use of a Head-Mounted Display: Sex Differences in the "Driver–Passenger" Effect

Introduction

Among users of interactive technologies, motion sickness is widely reported. For head-mounted displays (HMDs), this type of motion sickness is often referred to as cybersickness. Typically, the risk of motion sickness is greater during applications that feature virtual locomotion (i.e., movement of the observer relative to a virtual world) and is less common in applications that do not include virtual locomotion (e.g., Bruder et al., 2012; Munafo et al., 2017; Nilsson et al., 2018).

A common example of virtual locomotion is virtual driving. In many cases, users control virtual vehicles: they are drivers. In other cases, users merely observe the motion of virtual vehicles; in effect, they are passengers. Both physical and virtual vehicles are associated with the Driver–Passenger effect, in which the risk of motion sickness typically is greater for passengers than for drivers (e.g., Rolnick and Lubow, 1991; Dong et al., 2011). In this chapter, the final component of a larger study of sex differences in the driver–passenger effect in HMDs is reported. Earlier reports presented data on the incidence and severity of motion sickness (Chapter 2) and on standing body sway prior to HMD exposure (Chapter 3). In this chapter, the focus was on seated postural activity during exposure to a virtual vehicle presented through an HMD.

Postural Precursors of Motion Sickness During Exposure

The postural instability theory of motion sickness predicts that the quantitative kinematics of postural activity will differ between persons who state that they are motion sick and persons who state that they are not motion sick, and that these differences should exist before the onset of motion sickness (Riccio and Stoffregen, 1991). In the empirical literature, this prediction has been operationalized in terms of relations between quantitative measures of postural activity (i.e., continuous variables) and the incidence of motion sickness. In most tests, motion sickness incidence has been a dichotomous variable, with individual participants being classified as being either well or sick. Several studies have investigated the kinematics of postural activity during exposure to potentially nauseogenic motion. Most have used a method in which participants were instructed to discontinue immediately if they experienced any symptoms of motion sickness, however mild. This instruction is given repeatedly (e.g., during the consent process and before each exposure trial). In addition, participants are informed that they may discontinue participation at any time for any reason, and that there is no penalty for early discontinuation. These aspects of the design remove motivation for false positives (i.e., feigning motion sickness as an excuse to discontinue) and ensure that all postural data precede the onset of any subjective symptoms of motion sickness (e.g., Stoffregen and Smart, 1998; Dong et al., 2011; Stoffregen et al., 2017).

Using this method, researchers have identified postural precursors of visually induced motion sickness in laboratory devices (e.g., Stoffregen et al., 2010; Koslucher et al., 2014, 2016a; Li et al., 2018; Walter et al., 2019), in desktop virtual environments (e.g., Stoffregen et al., 2008, 2017; Dong et al., 2011; Chang et al., 2017), in handheld devices (Stoffregen et al., 2014), in projection video systems (e.g., Villard et al., 2008; Palmisano et al., 2018), and in HMDs (e.g., Merhi et al., 2007).

During exposure to virtual environments, postural activity evolves; that is, it changes over time. This effect has been documented in a wide variety of studies (e.g., Stanney et al., 1998; Stoffregen et al., 2010; Koslucher et al., 2016a). In a logically distinct effect, some studies have identified statistically significant interactions between the duration of virtual environment (VE) exposure and the subsequent development of motion sickness (e.g., Villard et al., 2008; Stoffregen et al., 2010, 2014; Koslucher et al., 2016a). This study expected to replicate these empirical effects.

Sex Differences in Postural Precursors of Motion Sickness

A common observation is that susceptibility to motion sickness differs between the sexes. In both field research and in the laboratory, women typically are more susceptible than men (e.g., Lawther and Griffin, 1988; Koslucher et al., 2015). Separately, both laboratory and population studies have found that the kinematics of standing body sway differ between the sexes (e.g., Era et al., 2006; Kim et al., 2010). Recent research has revealed that these two effects are related; that is, that postural precursors of motion sickness are different for women and men, with differences that often are qualitative. Several studies have found sex-specific postural precursors of motion sickness in standing body sway prior to exposure to any motion stimuli (e.g., Koslucher et al., 2016a; Munafo et al., 2017; Chapter 3 of this dissertation). Koslucher et al. (2016a) found this to be the case during exposure to nauseogenic motion. In this chapter, the first assessment of possible sex differences in postural precursors of motion sickness during seated exposure to virtual locomotion in an HMD was conducted.

Postural Precursors and the Driver–Passenger Effect

Arcioni et al. (2018; see also Risi and Palmisano, 2019) exposed participants to a virtual environment through an HMD. All participants controlled their own motion within the virtual environment. The authors measured standing body sway before HMD exposure, and in these data, they identified postural precursors of (subsequent) motion sickness. Arcioni et al. and Risi and Palmisano included both women and men, but the authors did not analyze for possible sex differences in postural precursors of motion sickness. Munafo et al. (2017) compared women and men, but measured postural activity only prior to exposure to the virtual environment. In addition, in their study, all participants controlled virtual locomotion.

Dong et al. (2011) examined the Driver–Passenger effect in virtual vehicles as presented to seated participants through a desktop video monitor. Using a yoked-control design (cf. Rolnick and Lubow, 1991), one member of each pair of participants (the Driver) drove a virtual vehicle (i.e., played the driving video game), while their performance was recorded. This recording was replayed and viewed by the other member of the pair (the Passenger). This design ensured that visual motion stimuli were identical for the two members of each pair: exposure to the game differed only in that one participant controlled the virtual vehicle, whereas the other did not. The results revealed that the incidence of motion sickness was greater among Passengers than among Drivers, consistent with the Driver–Passenger effect. Dong et al. also recorded the kinematics of the head and torso as seated participants were exposed to the video game. Patterns of postural activity were found to differ between Drivers and Passengers and, separately, between participants who later reported motion sickness, and those who did not. In this chapter, new questions about relations between postural precursors of motion sickness, the Driver–Passenger effect, and sex differences were asked.

Focus of This Chapter

The present chapter was modeled on Dong et al. (2011), in terms of a focus on head and torso movement of seated participants during exposure to a driving video game, either as drivers or as passengers. Like Dong et al., a yoked-control design in which one member of each pair of participants played a driving game (i.e., drove a virtual automobile) was used. A recording of that performance was viewed (in a separate session) by the other member of the pair. Thus, the two members of each pair were exposed to identical vehicle trajectories, but the risk of behavioral contagion was minimized. The present chapter differed from Dong et al. in several respects. First, a different driving video game was used. Second, the game was presented through an HMD, rather than being presented through a desktop interface. Third, this study used a crossed manipulation of vehicle control (i.e., Drivers vs. Passengers) with a manipulation of sex: half of the participants were men, whereas half were women. Independent measures of motion sickness incidence and symptom severity from this sample were reported in Chapter 2, where it was found that the incidence of motion sickness did not differ between Drivers and Passengers or between women and men. That is, they did not replicate either the classical Driver–Passenger effect or commonly reported sex differences in susceptibility. This dissertation project was the first assessment of the Driver–Passenger effect in an HMD, as well as being the first study of sex differences in the control of virtual vehicles. It is possible that unique characteristics of HMDs may minimize the Driver–Passenger effect, while the dynamics of virtual vehicles may tend to suppress sex differences in the incidence of motion sickness (for a discussion, see Chapter 2). In this chapter, the investigation of the kinematics of head and torso movement as seated participants were exposed to the driving video game, as presented in Chapter 2 is investigated. Previous studies have found differences in postural precursors of motion sickness between groups (e.g., people with vs. without experience driving physical vehicles) even when groups did not differ in motion sickness incidence or severity (e.g., Stoffregen et al., 2017).

Postural activity typically changes over time during exposure to virtual environments, and postural precursors of motion sickness often vary as a function of exposure duration (e.g., Dong et al., 2011; Chang et al., 2017; Stoffregen et al., 2017). Following these studies, data on postural kinematics was separated into three non-overlapping Time Windows, which allowed the experimenters to evaluate possible changes in postural activity as a function of exposure duration.

The experimenter predicted that postural activity would differ between Drivers and Passengers and between women and men. The primary prediction was that differences in postural precursors of motion sickness between Drivers and Passengers would, themselves, be modulated by sex. Within these interactions, the experimenter did not make predictions about specific contrasts. For this reason, the experimenter does not a report post-hoc contrasts on statistically significant effects.

Method

Participants

As noted in Chapter 2, the experimenter analyzed data on 79 participants. Some of those participants were not included in the present analysis (see the Results section for details). The present analysis included data from 65 individuals (32 women and 33 men), who participated in exchange for course credit. Participants ranged in age from 18 to 36 years (mean = 21.55 years, SD = 3.04 years), in height from 1.51 to 1.94 m (mean = 1.73 m, SD = 0.10 m), and in weight from 47.63 to 104.33 kg (mean = 72.19 kg, SD = 12.22 kg). The research protocol (STUDY00001875) was approved in advance by the IRB of the University of Minnesota.

Apparatus

Participants wore the Oculus Rift CV1. The device comprised a lightweight (0.360 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with 1,080 × 1,020 resolution, yielding a 100° horizontal field of view. A lens located in front of each display rendered display content at optical infinity.

A magnetic tracking system (Fastrak; Polhemus, Colchester, VT) was used to record postural activity. Sensors were worn at the head and torso (as described below), and each was sampled at 60 Hz. For each sensor, data on movement in the anterior–posterior (AP) and mediolateral (ML) axes was collected.

Procedure

Informed consent was gathered from each participant. Participants were informed that they could discontinue at any time, for any reason, without penalty. Following previous studies (e.g., Stoffregen and Smart, 1998; Merhi et al., 2007; Stoffregen et al., 2008, 2010; Dong et al., 2011; Koslucher et al., 2015), an independent assessments of the incidence of motion sickness and the severity of symptoms was used (for details, see Chapter 2). To assess motion sickness incidence, participants answered a forced-choice, yes/no question, *Are you motion sick?* Participants were instructed (both verbally and on the consent form) to discontinue the experiment immediately if they experienced any motion sickness symptoms, however mild. After completion of the consent process, a pre-exposure assessment of motion sickness incidence and severity was conducted, after which standing body sway while participants performed some simple visual tasks was conducted, as reported in Chapter 3.

Following the assessment of standing posture, participants sat on a stool that did not rotate and had no wheels and were fitted with a sensor from the magnetic tracking system, which was attached, using cloth medical tape, between the shoulder blades, at the base of the neck. Another sensor was attached to the Oculus headset. Participants donned the Oculus headset and were exposed to Assetto Corsa, a commercial driving game. Each Driver drove a Ferrari 458 Italia on the Highlands Long Track (Figure 4-1).

Figure 4-1: Overhead representation of the racetrack. The length of the simulated track was 12.19 km.

Details of the driving game were reported in Chapter 2. During exposure to the video game, a between-participants, yoked-control design, was used with individual Passengers yoked to individual Drivers. Participant pairs were sex-matched: men with men and women with women. Participants played or viewed the game for up to 15 min. Data on head and torso motion were collected continuously. Additional details of the yoked-control procedure are reported in Chapter 2.

After completing the 15-min game exposure, or after discontinuation (whichever came first), motion sickness incidence and severity was again assessed. Participants who answered yes to the forced-choice, yes/no question, *Are you motion sick?* were assigned to the sick group. All others were assigned to the well group.

Analysis of Head and Torso Movement

Postural activity can be characterized in terms of spatial magnitude (i.e., spatial structure), but it can also be characterized in terms of temporal dynamics (i.e., temporal structure). Recent years have seen the development of a wide array of dependent variables that assess different aspects of the temporal dynamics of the kinematics of human movement. Many widely used parameters are derived from general physical processes and do not have an a priori or intrinsic relation to animate movement. For example, stabilogram diffusion analysis (e.g., Collins and De Luca, 1993) is derived from models of the movement of gas molecules and has no intrinsic relation to the physical structure of the body. One relatively new parameter is the multifractality of movement. Several scholars have argued that multifractality may be a fundamental property of animate movement, and that, as such, measures of multifractality may be more meaningful than measures of other aspects of temporal dynamics (Kelty-Stephen et al., 2013; Palatinus et al., 2014). Several studies have documented the existence of multifractality in standing body sway (Thurner et al., 2000; Shimizu et al., 2002; Ihlen et al., 2013; Munafo et al., 2016). Other studies have shown that postural precursors of motion sickness can occur in the multifractality of postural activity (e.g., Koslucher et al., 2016a; Munafo et al., 2017; See Chapter 3 of this Dissertation).

Separate evaluations of the spatial magnitude and multifractality of movement were conducted. The spatial magnitude of postural activity in terms of positional variability was evaluated, which the experimenter defined operationally as the standard deviation of position. Multifractal detrended fluctuation analysis, or *MF-DFA*, was used to evaluate the multifractality of postural activity (e.g., Kantelhardt et al., 2002; Ihlen et al., 2013; Munafo et al., 2016). *MF-DFA* is an extension of detrended fluctuation analysis, or *DFA* (Lin et al., 2008). *MF-DFA* has been used in the assessment of postural sway in a variety of contexts (e.g., Munafo et al., 2016). Detrended fluctuation analysis assumes that fluctuations in a time series are homogeneous (Ihlen and Vereijken, 2010), but this assumption typical is not met in data on human movement: multifractal fluctuations are interdependent and heterogeneous. The heterogeneous nature of multifractal fluctuations can be revealed in the range of the singularity exponent, *h(q)* (Ihlen, 2012). The width of this range is an index of the degree (or amount) of multifractality in a time series. The range of *h(q)* values is known as the *singularity spectrum* or the *spectrum*. The wider the spectrum, the more multifractal is the movement (Kelty-Stephen et al., 2013). For each trial, inferential statistics on the width of the singularity spectrum was conducted. The width of the spectrum using open source code for MATLAB was obtained (MFDFA1; Ihlen, 2012). Following Munafo et al. (2016), the experimenter selected a minimum scaling range of 16 data points with 19 evenly spaced increasing segment sizes to a maximum of the length of the time series. This range was the same for each time series.

Exposure duration varied between participants, as reflected in variations in discontinuation time, and in the fact that some participants completed the 15-min protocol. Separate repeated measures ANOVAs on positional variability and the width of the multifractal spectrum was conducted. For each ANOVA, the factors were Time Windows (W1, W2, W3), Segment (head vs. torso), Body Axis (AP vs. ML), Sex (women vs. men), Control (drivers vs. passengers), and Sickness Groups (well vs. sick). Time Windows, Segment, and Body Axis were within-participants factors, whereas Sex, Control, and Sickness Groups were between-participants factors.

Results

As reported in Chapter 2, the overall incidence of motion sickness was 43% (34/79). Data on symptom severity were also reported in Chapter 2.

The kinematic data from three participants (one well, two sick) was excluded because of technological difficulties. Of the remaining 32 participants in the sick group, 11 discontinued after <6 min of game play. For this reason, these eleven participants were excluded from movement analysis. For the remaining 21 participants in the sick group, the mean exposure to the game was 620.64 ± 190.01 s. Following Chang et al. (2017), the experimenter defined time windows for the well groups based on the mean exposure time of participants in the sick group. Accordingly, Window 1 comprised the first 120 s of game play, Window 2 ran from 251 to 371 s, and Window 3 ran from 501 to 621 s.

Positional Variability

The results are summarized in Table 4-1, which details Factors, F-values, p-values, and values of partial $\eta 2$. For positional variability, the main effect of Segments was significant. Positional variability for the head (M = 1.17 cm, SE = 0.08 cm) was greater than that for the torso (M = 0.76 cm, SE = 0.06 cm). The main effect of Time Windows was significant (Window 1 mean = 1.06 cm, SE = 0.07 cm; Window 2 mean = 0.91 cm, SE = 0.08 cm; Window 3 mean = 0.93 cm, SE = 0.07 cm).

Table 4-1: Statistically significant effects from analysis of variance.

	Positional Variability		
	F	***p***	***Partial η^2***
Segments	(1, 57) = 74.53	<.001	0.57
Time Windows	(2, 114) = 3.99	.021	0.07
Segment × Time Windows	(2, 114) = 6.49	.002	0.10
Body Axis × Time Windows	(2, 114) = 9.55	<.001	0.14
Body Axis × Time Windows × Control × Sex	(2, 114) = 5.07	.008	0.08
Body Axis × Time Windows × Control × Sickness Groups	(2, 114) = 3.41	.036	0.06
Segment × Control	(1, 57) = 5.99	.018	0.10
Body Axis × Segment	(1, 57) = 19.29	<.001	0.25
Body Axis ×	(1, 57) = 6.25	.015	0.10

Segment × Sex × Sickness Groups			
Body Axis × Segment × Control × Sex × Sickness Groups	(1, 57) = 4.40	.04	0.07
Width of the Multifractal Spectrum			
	F	***p***	***Partial*** $\boldsymbol{\eta^2}$
Control	(1, 57) = 7.24	.009	-0.11
Body Axis × Segment	(1, 57) = 4.80	.033	0.08

There were several significant interactions involving the Time Windows factor. A stand-alone effect was the significant Segment × Time Windows interaction. As shown in Figure 4-2, motion of the head and torso changed differently over time (i.e., across Time Windows).

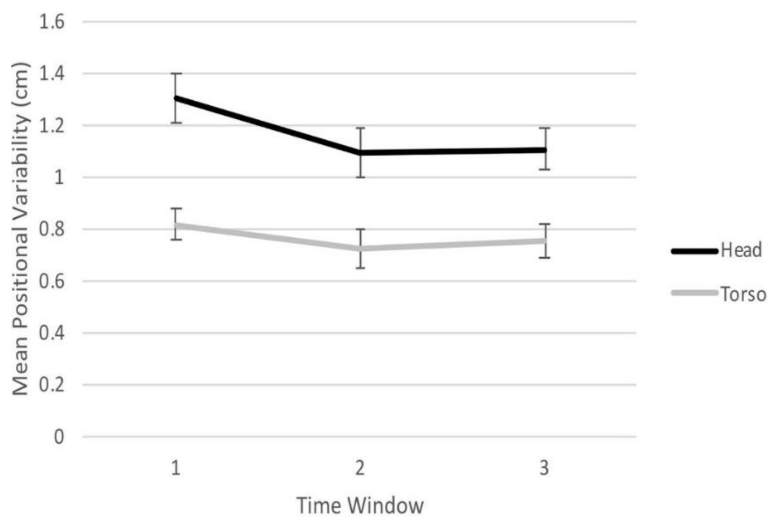

Figure 4-2: Positional variability, illustrating the statistically significant interaction between Body Segment (head, torso) and Time Windows.

For the torso, changes across Time Windows were not significant. The Body Axis × Time Windows interaction was significant. This interaction was subsumed in two higher-order interactions. The Body Axis × Time Windows × Control × Sex interaction was significant (Figure 4-3). In addition, the Body Axis × Time Windows × Control × Sickness Groups interaction was significant (Figure 4-4).

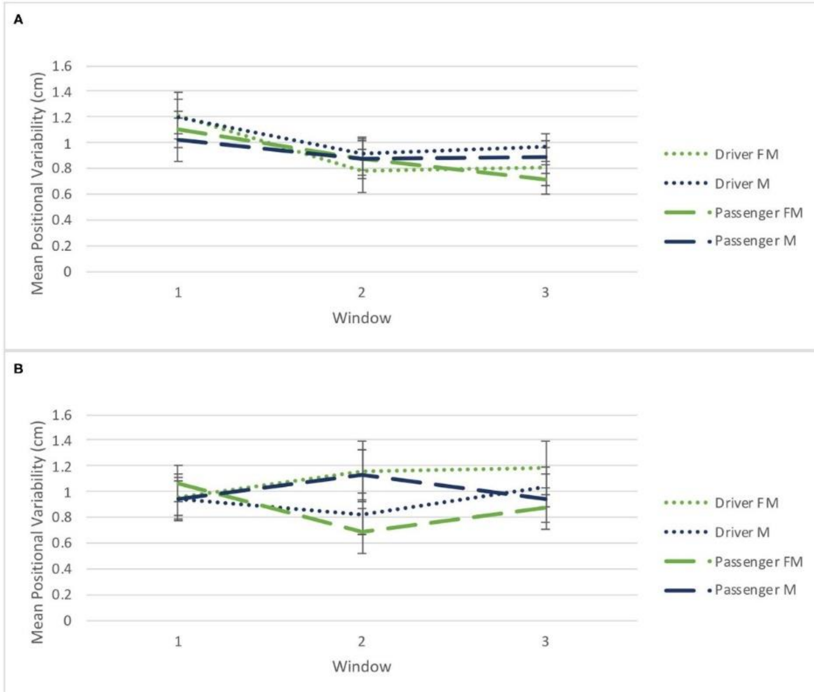

Figure 4-3: Positional variability, illustrating the statistically significant interaction between Body Axis (anterior–posterior, mediolateral), Sex, Control (drivers, passengers), and Time Windows. (A) Movement in the mediolateral axis. (B) Movement in the anterior–posterior axis.

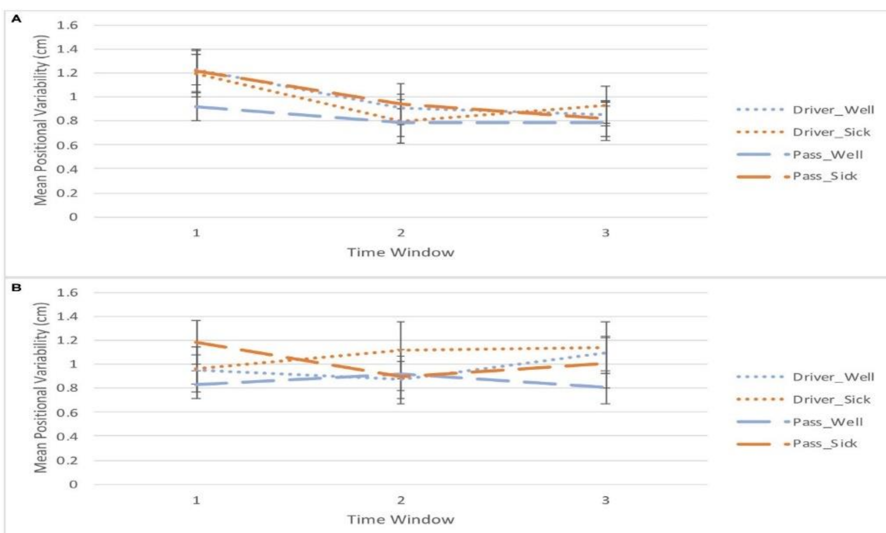

Figure 4-4: Positional variability, illustrating the statistically significant interaction between Body Axis (anterior–posterior, mediolateral), Control (drivers, passengers), Time Windows, and Sickness Groups. (A) Movement in the mediolateral axis. (B) Movement in the anterior–posterior axis.

Several significant interactions did not include the Time Windows factor. The Segment × Control interaction was significant, as was the Body Axis × Segment interaction which was significant. In addition, the Body Axis × Segment × Sex × Sickness Groups interaction was significant. These interactions were subsumed in a statistically significant 5-way interaction between Body Axis, Segment, Control, Sex, and Sickness Groups (Figure 4-5). There were no other significant differences.

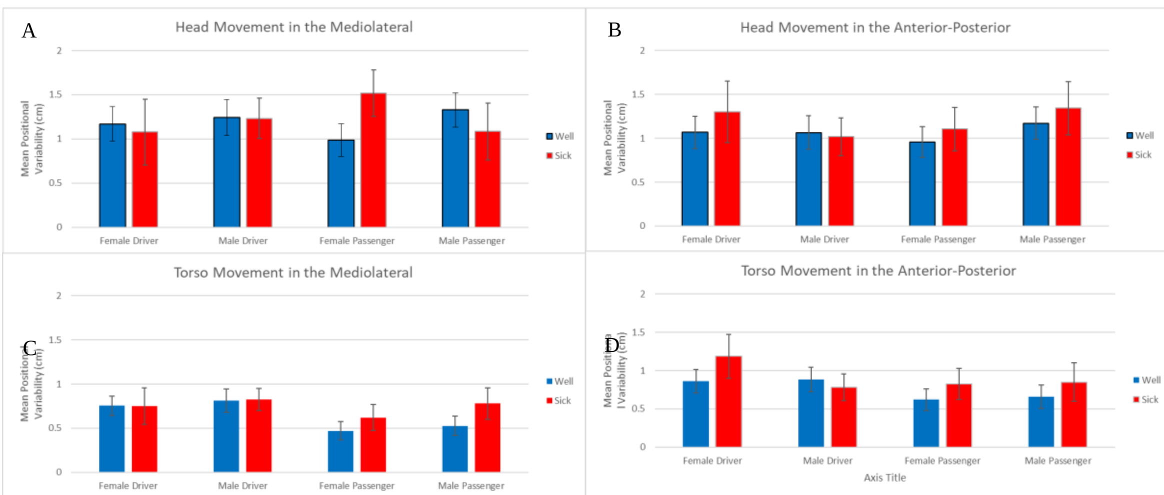

Figure 4-5: Positional variability, illustrating the statistically significant interaction between Body Axis (anterior–posterior, mediolateral), Segment (Head, Torso), Sex, Control (drivers, passengers), and Sickness Groups. (A) Head movement in the mediolateral axis. (B) Head movement in the anterior–posterior axis. (C) Torso movement in the mediolateral axis. (D) Torso movement in the anterior–posterior axis.

Width of the Multifractal Spectrum

The results are summarized in Table 4-1. For the width of the multifractal spectrum, the main effect of Control was significant. The multifractal spectrum was wider among Passengers (M = 0.36, SE = 0.02) than among Drivers (M = 0.30, SE = 0.02). In addition, the Body Axis × Segment interaction was significant (head AP M = 0.31, SE = 0.01; head ML M = 0.32, SE = 0.014; torso AP M = 0.36, SE = 0.02; torso ML M = 0.32, SE = 0.02). There were no other significant effects.

Discussion

Seated participants were exposed to a virtual vehicle in a driving video game that was presented through an HMD. The experimenter covaried sex (women vs. men) control of the virtual vehicle (drivers vs. passengers) and motion sickness status (well vs. sick, as reported in Chapter 2). In this chapter, movement of the head and torso during game exposure was examined. Several effects that were independent of motion sickness status were found. Some of these replicated common findings in the literature, whereas others were novel. The principal result of this chapter was the identification of postural precursors of motion sickness. Two statistically significant interactions revealed that postural precursors of motion sickness differed between drivers and passengers and between women and men. These results are discussed in turn.

Movement Independent of Motion Sickness

The main effect of Segment was significant for the positional variability of postural activity, but this effect was subsumed in the significant Segment × Time Windows interaction (Figure 4-2). The nature of the interaction was unusual, in that movement of both the head and torso declined across Time Windows. This pattern contrasts with previous studies, in which postural activity has tended to increase over time (e.g., Merhi et al., 2007; Villard et al., 2008; Dong et al., 2011). The Segment × Body Axis interaction was also significant for the width of the multifractal spectrum. That is, relations between body segments and body axes influenced the orthogonal variables of positional variability and movement multifractality. A similar effect was reported by Walter et al. (2019) who exposed standing participants to oscillation of the visual environment along the line of sight.

For positional variability, the Body Axis × Time Windows interaction was significant; however, this interaction was subsumed in the significant Body Axis × Sex × Control × Time Windows interaction (Figure 4-3). Sex differences are a common feature of the kinematics of standing body sway (e.g., Era et al., 2006; Kim et al., 2010). In the present chapter, participants were seated, which made it possible for the experimenter to evaluate the possibility that there might be sex differences in the control of seated postural sway. The experimenter is not aware of any previous research on sex differences in seated postural activity. Accordingly, the effect illustrated in Figure 4-3 appears to be novel.

The main effect of Control was significant for the width of the multifractal spectrum, confirming the experimenter's prediction. The multifractal spectrum was wider (that is, postural activity exhibited a greater degree of multifractality) for Passengers than for Drivers. Differences in postural activity between seated Drivers and Passengers in virtual vehicles have been reported in previous studies in which virtual vehicles were presented via a desktop monitor. Dong et al. (2011) found that postural activity of Drivers and Passengers differed in terms of both the positional variability and temporal dynamics of the head and the torso. A similar effect has been reported for seated participants who controlled the gait of a virtual avatar vs. participants who merely watched recorded locomotion of the avatar (Chen et al., 2012). Chen et al. also found control-related differences in the positional variability of the torso and the temporal dynamics of the head. That movement might differ between Drivers and Passengers is not surprising. Because Drivers control the virtual vehicle, their postural adjustments related to vehicle motion can be anticipatory. For Passengers, postural adjustments for motion of the virtual vehicle must be compensatory (Dong et al.; Stoffregen et al., 2017).

Postural Precursors of Motion Sickness

Postural precursors of motion sickness in the positional variability of the head and torso were identified. One such effect was a statistically significant Body Axis × Time Windows × Control × Sickness Groups interaction (Figure 4-4). This interaction reveals that the temporal evolution of postural precursors of motion sickness differed between Drivers and Passengers. This finding is novel. Dong et al. (2011) found that the temporal evolution of movement differed over time (i.e., across Time Windows) between Drivers and Passengers. In a separate effect, they found that the temporal evolution of movement differed between the well and sick groups; however, they found no evidence of any interaction between these factors. In the present chapter, the novel identification of this interaction may be related to the fact that the driving game was presented via an HMD, whereas in Dong et al., the driving video game was presented on a desktop monitor.

The experimenter's primary prediction was that there would be statistically significant interactions that would include the factors Sickness Groups, Sex, and Control. This prediction was confirmed in the statistically significant Body Axis × Segment × Control × Sex × Sickness Groups interaction (Figure 4-5). This effect reveals, for the first time, that sex can interact with vehicle control in determining postural precursors of motion sickness.

To summarize, in two statistically significant interactions, postural precursors of motion sickness differed between Drivers and Passengers (Figure 4-4 & Figure 4-5). In one of these interactions, postural precursors of motion sickness that differed between Drivers and Passengers also differed between women and men (Figure 4-5). Several studies have identified sex differences in postural precursors of motion sickness (Koslucher et al., 2016a,b; Munafo et al., 2017), but this is the first demonstration that sex differences in postural precursors of motion sickness can differ between drivers and passengers. These effects confirm a prediction of the postural instability theory of motion sickness (Riccio and Stoffregen, 1991) that the kinematics of movement should differ between individuals who (later) report motion sickness and those who do not, and that these differences should exist before the onset of any subjective symptoms of motion sickness. The postural instability theory predicts that any factor that influences the control of posture can modulate postural precursors of motion sickness. The present results demonstrate that such individual differences can be situational, or task related (i.e., Drivers vs. Passengers; cf. Slobounov and Newell, 1994; Stoffregen et al., 1999), or structural (i.e., women vs. men). These results are consistent with broader developments in the study of human movement, such as the claim that the subtle kinematics of movement may be unique to each individual (e.g., Slowinski et al., 2016). Other theories of motion sickness etiology (e.g., Reason, 1978; Oman, 1982) make no predictions about how postural precursors of motion sickness might be modulated by either situational or structural factors.

Interpupillary Distance: Cause or Correlate?

The Oculus Rift system fits persons with interpupillary distance (IPD) in the range 58–71 mm. Most adults fall within this range; however, 30% of adult women have IPD <59 mm (Stanney et al., 2020). Stanney et al. (2020) found that cybersickness was correlated with the "goodness" of IPD fit. However, based on this correlational finding, they did not claim that IPD played a causal role in cybersickness. If IPD were a causal factor in motion sickness among HMD users, then one would expect to see higher rates of sickness among populations that tend to have smaller IPD. One such population is children, who often are enthusiastic users of HMD systems. Thus, if motion sickness is caused by inappropriate matching between HMD design capabilities and users' IPD, then one would expect that HMD-related motion sickness would be especially common among children. The experimenter knows of no evidence for differential rates of HMD-related sickness between children and adults. There is also an issue of etiology. A correlation between IPD and motion sickness susceptibility does not, by itself, imply any particular etiological interpretation. On the one hand, the discrepancy might be interpreted as a source of sensory conflict, such that the correlation between IPD and cybersickness might have a causal link through the sensory conflict theory of motion sickness (Reason, 1978; Oman, 1982). However, an interpretation in terms of sensory conflict is not mandatory. Different causal linkages can be proposed. It might be, for example, that improper fit of HMD headsets can undermine stable control of the body, which is more likely to have a causal relation to cybersickness. The experimenter predicts that correlations should be stronger between motion sickness and postural kinematics than between motion sickness and IPD.

Conclusion

The postural activity of seated participants during exposure to a driving video game presented through an HMD was examined. Sex (women vs. men), vehicle control (Drivers vs. Passengers), and motion sickness status (as reported in Chapter 2) were covaried. Analysis of the positional variability of head and torso movement revealed differences between Drivers and Passengers in the temporal evolution of postural precursors of motion sickness. In a separate effect, postural precursors of motion sickness that differed between Drivers and Passengers co-varied as a function of sex. These results are in agreement with the general hypothesis that motion sickness is preceded by patterns of postural activity that differ between individuals who (later) report motion sickness and those who do not. In addition, these results reveal that the nature of postural precursors of motion sickness can differ between the sexes and between Drivers and Passengers. In general, the results are consistent with predictions derived from the postural instability theory of motion sickness (Riccio and Stoffregen, 1991).

Chapter 5: General Discussion

In this research, the "driver-passenger" using an HMD was examined. In the introduction, four goals and four hypotheses were discussed, which were set to be answered with this project. In the following subsections, each of these goals and hypotheses will be discussed.

Goal 1

The first goal of this research project was to understand how the driver-passenger effect would differ between men and women. The hypothesis associated with this goal was that females, regardless of driver/passenger condition, would be more likely to become cybersick than males and would have higher severity of symptoms than males. To test this hypothesis, 41 females and 38 males were recruited. The reason for the additional three females was because they discontinued after less than 60 s and therefore were replaced (See Methodological Section of Chapter 2 for additional description).

The incidence data showed that 18/41 (44%) females became cybersick compared to 16/38 (42%) males. These rates did not differ, $\chi 2 = 0.26$, $p > .05$. The severity of symptoms showed that following game play (SSQ-2, or SSQ-3), scores did not differ between the men (mean = 38.58, SD = 30.84) and women (mean = 40.41, SD = 33.26), $U = 741.5$, $p = .71$.

While the hypothesis was not supported, it was found that of the drivers that discontinued, females (mean = 191.3 s, SD = 68.2 s; 95% CI = 50.9–331.8 s) discontinued earlier than males (mean = 457.7 s, SD = 77.3 s; 95% CI = 297.4–615.9 s). This effect, while modest, suggests that the driver-passenger effect may differ amongst males and females, thereby providing some support for this initial hypothesis.

Goal 2

The second goal of this project was to examine whether the driver-passenger effect would occur in an HMD. To answer this goal, the 79 participants were assigned to either the driver (41 participants) or the passenger (38 participants) group. The hypothesis that was associated with this goal was that participants in the passenger group will have a higher incidence and a higher severity of cybersickness.

For drivers, the incidence of motion sickness was 49% (20/41). For passengers, the incidence was 37% (14/38). These rates did not differ, $\chi 2 = 1.15$, $p > .05$. Symptom severity also did not differ amongst these groups. For drivers it was found following game play (SSQ-2, or SSQ-3), scores did not differ between Drivers (mean = 41.51, SD = 32.90) and Passengers (mean = 37.40, SD = 31.13), $U = 726.5$, $p = .61$. Therefore, the hypothesis proposed in Chapter 1 was not supported by this current study.

Goal 3

The third goal was to investigate postural precursors of cybersickness. As discussed in the introduction, the Postural Instability theory suggests that a person should display distinctive patterns of postural activity that differ from individuals that later report symptoms of motion sickness. The hypothesis for this goal is as follows: there will be statistically significant interactions that include Sickness Groups, Sex, and Control in the postural movement patterns prior to donning the HMD. To answer this hypothesis, 79 participants stood on a force plate while they conducted two visual tasks prior to donning the HMD. This hypothesis was supported as the Sex × Sickness Groups × Control interaction was found to be significant, $F(1, 70) = 4.14$, $p = .046$, partial $\eta 2 = .05$. These results confirm that postural precursors of cybersickness would differ between the sexes.

Goal 4

The fourth, and final goal, was to study how postural activity during exposure differs between those that become cybersick and those that do not. To address this goal, postural data gathered from the head and torso of 65 participants. The hypothesis associated with this goal was as follows: there will be statistically significant interactions that include Sickness Groups, Sex, and Control in the postural movement patterns while wearing the HMD. What was found was that statistically significant 5-way interaction between Body Axis, Segment, Control, Sex, and Sickness Groups $F(1, 57) = 4.40$, $p = .04$, partial $\eta 2 = .07$. These findings support the hypothesis proposed in Chapter 1 and provide additional support for the Postural Instability theory.

Significance

This project, to the experimenter's knowledge, was the first to investigate sex differences in motion sickness relating to drivers and passengers of either physical or virtual vehicles. While this project was not able to replicate this effect using an HMD, it found that of the drivers that discontinued, females discontinued earlier than males. Thus, providing modest evidence for sex differences in relation to the driver passenger effect.

While this project was not able to replicate the driver passenger effect, it did further accentuate the issue of cybersickness with HMDs. In this project, it was found that 34/79 (43%) participants became cybersick. Twenty-nine of these participants discontinued without completing the15-minutes of exposure. The overall mean time of discontinuation for these 29 participants was 360 s (SD =226.51). This short duration is problematic and stymies the practical applications of VR, as it would be difficult to argue the benefits of using these devices if a subset of users would not be able to don the headset for a short time without an adverse event.

Additionally, this project found additional evidence for the Postural Instability theory. Cybersickness research is typically assessed using questionnaires (e.g., SSQ). The problem with questionnaires is that it is limited. Questionnaires are subjective and require the user to assess their own well-being. Regarding the latter point, certain subjects may overrate their symptoms, while others may underrate. However, with repeated support for the Postural Instability theory, it appears that body sway characteristics can be a sensitive objective predictor of cybersickness; thus, offering an alternative to questionnaires.

Application

The importance of having an objective predictor is that it offers a strategy for the mitigation, whereby interventions are implemented before the onset of subjective symptoms of cybersickness. Predictive models could be developed using this information on body sway, as a way to adjust visual content in real-time as a way to assuage cybersickness. Some recent research has shown that adding certain elements to a virtual environment can reduce cybersickness. Cao, Jerald, and Kopper (2018) showed that adding a stable reference frame can reduce discomfort. An additional method includes modifying the virtual environment during rotations (Farmani & Teather, 2018; Budhiraja et al. 2017). These various approaches of adapting the virtual environment could be combined and occur in real-time, thereby allowing users with a high susceptibility to use VR devices with a reduction in cybersickness.

Suggestion for Future Research

This current project displayed how body sway can be an objective predictor for cybersickness research. In future research, it is important to explore if predictive models could be developed for cybersickness research. Such predictive models have been developed in the past for motion sickness studies conducted in moving rooms (Smart et al., 2002). In Smart et al. (2002), they developed a predictive model that could correctly distinguish between sick and well groups with 80% accuracy. Such models could be developed for cybersickness application and be integrated into a virtual environment. Kinematic data needed by these models could be gathered by using the VR equipment. For instance, head movement could be gathered by using data gathered by the HMD. Using this kinematic data, these models would ideally subtly adapt the virtual environment. This approach would allow the user to continue without adverse events. This would potentially mean that a patient using VR for treatment would be able to complete their VR session with a reduction of cybersickness outcomes.

Virtual Environment Adaptation

Nonetheless, in order to understand how to modify the virtual environment, it is imperative to understand what factors heighten cybersickness. Thus far, it is known that certain elements of a virtual environment will increase the likelihood of cybersickness. For instance, maximum discomfort has been reported to occur during rotational movements (Trutoiu et al., 2009). Studies have shown that modifying the visual content during rotational movements, either by applying a Gaussian blur or a snap rotation method, can reduce discomfort (Budhiraja et al., 2017; Farmani & Teather, 2018).

However, one potential drawback with this method is it could impact the user experience, as well as a concept known as presence. Presence can be defined as follows: “subjective experience of being in one place or environment, even when one is physically situated in another” (Witmer & Singer, 1998). A potential compromise is to dynamically reduce the FOV in a subtle manner, so the user is unaware, thereby hopefully preventing a break in presence. This method of dynamically reducing the FOV in a subtle manner was explored by Farmani and Teather (2018), where they found, a majority of participants did not notice the dynamic changes in the FOV, and presence scores did not significantly differ when participants had an unaltered FOV compared to when they did have an altered FOV.

An additional way to modify the virtual environment is by manipulating optic flow. Optic flow can be described as the perceived visual motion of objects that are generated through an observer’s movements (Gibson 1966). Optic flow can be manipulated by varying texture density. That is to say, visual displays that contain a lot of details (optical density) often give rise to stronger subjective sensations of movement, or vection. Thus, if the level of details in the VE is reduced, then this likely will decrease vection.

Focusing on the latter factor, Davis, Nesbitt, Nalivaiko (2015) assessed cybersickness and the influence of texture density by using two different rollercoaster games. One rollercoaster was rich in detail, while the other one was not. Participants in the rich environment condition were significantly more likely to experience cybersickness than those participants in the less detailed environment. It should be noted that their study used rollercoasters from two different commercial games and thus the visual content presented to the participants was not similar. The fact they used two different roller coasters introduces a confounding variable as these differences may be attributed to an alternate explanation. For instance, a more detailed VE will have a greater processing lag than a less complex VE (Papadakis et al. 2011).

To address this limitation, a study could be designed that controls for these computational differences. If a study were to find a difference between these two conditions using a between-subject design, a follow-up study could be conducted using a within-subject design to better understand the impact such a reduction in texture density may have on the user experience. It is critical to know the impact on the user experience, as VR is often well regarded for its ability to immerse users into a detailed and realistic virtual environment. This within-subject design could follow a similar experimental design that was conducted in Farmani and Teather (2018) study.

Tertiary Measures

In addition to using kinematic data, developed predictive models could use other user factors such as eye gaze data, as well as physiological data. Focusing on the former, it has been suggested that gaze instability or uncontrolled eye movements can cause motion sickness (Riccio & Stoffregen, 1991). As the authors suggested that this inability to control eye movements can preclude one's ability to detect visual cues that can be used to control various actions, such as posture. Such an inability can lead to postural instability. While at first, it may appear that eye movements are unrelated to postural instability, it has been shown that posture can be altered by visual stimuli (Lee & Lishman, 1975). While this informational linkage has been hypothesized, there is limited research supporting this claim.

Besides eye gaze data, blink rate data could also be gathered. Kim et al. (2005) examined a participant's blink rate during exposure to a virtual environment via a projection system. Their results showed that as immersion time increased, so did the blink rate of their participants. They found a significant correlation between increasing blink rate and increasing scores on the SSQ. A similar finding was observed by Dennison et al. (2016), who used an HMD and found significant correlations between the average amount of blinks and the SSQ Oculomotor Score. Therefore, based on the results of these two studies, it appears blink rate could be a way to determine if someone is becoming cybersick or not.

To explore the validity of eye gaze and blink rates, a future study should be designed to collect eye gaze data and blink rates during VR exposure. Currently, there are a few options for VR headsets that come readily equipped with eye-tracking capabilities, such as the HTC Vive Pro Eye. An experiment could be designed to gather eye gaze and blink rate data from participants and examine if patterns differ between those that are classified as sick and those who are not.

In addition to gathering eye gaze and blink data, future cybersickness research could explore the correlation between certain physiological data measures and cybersickness. One measure that has shown the potential to distinguish between individuals who classified as sick and those who are not is heart rate data. For instance, Holmes and Griffin (2001) found an association between increasing subjective ratings of motion sickness and increasing heart rate when exposing subjects to an Optokinetic drum. A similar finding was shown in Nalivaiko et al. (2015) study, which found that participants that were classified between mildly and strongly nauseated based on their subjective symptoms had a significant increase in heart rate compared to the pre-exposure rates. However, a similar association was not seen with Gavgani, Nesbitt, Blackmore, and Nalivaiko (2017) study. These differences in results make it difficult to assess the sensitivity of this approach in determining participants that are cybersick; therefore, additional research is needed to understand whether or not heart rate data can be used to classify individuals that are becoming cybersick and those who are not.

An additional measure that could be gathered is galvanic skin response (GSR). There is some evidence of a correlation between GSR and cybersickness (Gavgani et al. 2017). However, Dennison et al., (2016) did not observe a relationship between GSR and cybersickness. Similar to heart rate, these differences in results make it difficult to assess the sensitivity of this physiological measure. Future research is needed to further understand the correlation between GSR and cybersickness.

Heart rate data and GSR can be non-invasively gathered by using upcoming wrist-based interaction methods (Facebook, 2021). Gathering data in this manner would avoid adding additional sensors, which may not be practical during actual use. By gathering physiological, eye, and kinematic data using pre-existing VR equipment the user would not be encumbered with sensors that are typically used to gather such data. Using these measures with a comprehensive understanding of what factors may alleviate cybersickness, a virtual environment can be adequately adapted to reduce the nauseogenic experience. This approach of adapting the virtual environment in real-time depending on a user's behavior would be meant as a way to ease a user susceptible cybersickness into VR.

Conclusion

In conclusion, cybersickness may be merely unfortunate in the context of entertainment applications, but it becomes a problem as VR extends to industrial and medical applications. One fact of particular significance is the fact females are more likely than males to become sick, which can yield de facto discrimination. This difference was shown in this current project with participants who discontinued early, the exposure time for female drivers was significantly less than for male drivers. This found sex difference suggests that this dissimilarity may be dependent on the task being performed in the virtual environment. Which can be problematic if certain tasks are related to one's job or medical treatment.

In addition to further shedding light on sex differences in cybersickness, this project also provided additional support for the Postural Instability theory. While mass adoption of VR may be impending, it is becalming to know that predictive models could potentially be developed using kinematic data to assuage cybersickness.

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